

Catcher's Mitt Final Report

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1 Executive Summary

Since the advent of the space age, more than thirty-five thousand man-made objects have been cataloged in orbit around the Earth by the U.S. Space Surveillance Network. Nearly fifteen thousand of those objects remain in orbit today, ninety-four percent of which are non-functioning space vehicles and orbital debris. These figures do not include the hundreds of thousands of objects too small to be detected and cataloged, but still large enough to pose a threat to operational satellites. Of most concern, collisions between orbital objects could potentially lead to a continuously growing debris population, thus further increasing the risk to operational satellites.

For several years spacefaring nations have recognized the mounting risk posed by orbital debris. It is a growing problem that already imposes probable costs on asset operators. Mitigation measures to minimize the generation of debris, such as limiting debris released during normal operations, reducing the potential for on-orbit breakups, and planning for post mission disposal, have been adopted by many countries in an attempt to slow the growth of the orbital debris population, with some success. However, current analysis and two recent, significant debris-generating events indicate that debris mitigation alone will not be sufficient to prevent continued growth of the debris population.

Several studies and lab experiments on debris removal have been conducted over the past several years. However, only now have technology and an operational imperative come together to make debris removal a realistic international objective.

The Catcher's Mitt study was conducted to evaluate the need for, and the technical feasibility of, reducing the amount of orbital debris via active removal. The Defense Advanced Research Projects Agency (DARPA) with support from the Orbital Debris Office at NASA reached out to the aerospace community through a U.S. Government roundtable series, a Request for Information (RFI), and an international conference in order to explore the full range of possible solutions. These concepts were evaluated by a team of experts in the field and condensed into a set of practical options to be considered for a new DARPA program.

Although there are many policy issues which need to be addressed related to orbital debris removal, the Catcher's Mitt study focused on the technical challenges of the problem. A variety of potential methods were examined for addressing the problem of orbital debris, and active debris removal was found to be required at some point to maintain an acceptable level of operational risk. Although projections show that it may take decades for the risk to become unbearable, this report outlines several reasons to begin development of a solution today.

A central finding of this study is that the development of debris removal solutions should concentrate on pre-emptive removal of large debris in both Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO). Although the greatest threat to operational spacecraft stems from medium debris (defined as 5 mm – 10 cm), no reasonable solution was found to effectively remove this size of debris object. Compliance with existing international debris mitigation guidelines coupled with the pre-emptive removal of the sources of future medium debris, is by far the most cost-effective strategy. For the LEO region, NASA has suggested that annually removing 5 to 10 of the largest objects with the greatest risk of collision could stabilize the current medium sized debris population when combined with improved post-mission spacecraft disposal rates.

Current design practices generally allow spacecraft to survive impacts with debris of 5 mm or less. Providing collision avoidance information to maneuverable spacecraft allows them to avoid larger debris, 10 cm and up. Armoring spacecraft to survive collisions with 5 mm to 10 cm sized debris is not economically feasible and is likely not technically feasible. Providing collision avoidance information to active spacecraft for the hundreds of thousands of these medium sized debris objects will only be of potential benefit to the subset of maneuverable spacecraft which can actually act upon that information. Even then, the information provided would have to be radically improved beyond current capabilities to avoid unnecessary avoidance maneuvers, which would rapidly deplete spacecraft lifetime fuel reserves. The key issue then is the stabilization or reduction of the population of medium debris. At this time the only feasible approach to this problem is to remove the sources of future medium debris by actively removing large objects from congested orbits.

Although it is clear that the debris spatial density (and collision risk) in GEO is lower than in LEO, the threat from failed spacecraft in that singular orbit can impose significant operational difficulties to assets the GEO belt. Conversely, technical solutions to large object removal in GEO can serve as stepping stones to a capability to refuel or even repair high value GEO assets.

The study also examined potential solutions for recovering after a space conflict in both LEO and GEO. This scenario was specifically examined due to the military need for a rapid debris removal solution in this situation and the associated technical difficulty. All examined solutions to this scenario imposed risks to operational assets or were not reasonable considering the current debris spatial density, however, neither of these concerns is likely an issue after a space conflict and therefore acceptable solutions may exist. However, given the low probability, high consequence nature of this scenario, it may be difficult to sustain a development program to address this particular problem.

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2 Catcher's Mitt Approach

2.1 Background

The accidental collision of a defunct Russian communications satellite (Cosmos 2251) and an operational Iridium satellite in 2009 accentuated a growing belief within the space community that orbital debris—once little more than an annoyance or curiosity—has become a serious operational concern. Moreover, the intentional destruction of the Fengyun-1C weather satellite by the Chinese military underscores the potential consequences (either intentional or unintentional) of a future conflict should it extend to the space domain. These events, coupled with an increase in the total amount of space debris due to normal satellite operations, have raised concerns that cascading orbital collisions will make parts of Low Earth Orbit (LEO) too dangerous and expensive for routine space operations. While most experts agree this possibility is, at the earliest, several decades off, the fact remains that orbital debris is a growing problem. However, until now Federal agencies have been hesitant to invest significant resources without an assigned debris removal mission¹. Likewise, a lack of economic incentives has resulted in little independent action from industry. Yet, failure to address this problem has significant implications for the success of future space missions due to the potential increased number of on-orbit collisions with nontrackable, yet lethal, debris fragments.

2.2 Study Objectives

To better understand the issues and challenges involved with removing man-made debris from earth orbit, DARPA conducted a study, known as Catcher's Mitt. This study was intended to address the increasing hazard from orbital debris faced by all U.S. and international space assets.

For several years spacefaring nations have recognized the mounting risk posed by orbital debris. The U.S. Space Surveillance Network (SSN) maintains a catalog of nearly fifteen thousand objects in orbit. This figure does not include hundreds of thousands of objects too small to be cataloged, but still large enough to pose a threat to operational satellites in orbit around the Earth, nor nearly 5,000 objects that are tracked but not correlated to a specific launch and thus not included in the "catalog".

Mitigation measures to minimize the generation of debris have been adopted by many countries in an attempt to slow the growth of the orbital debris population, with some success. However, two significant debris-generating events during the past two years have resulted in a significant increase in the number of debris objects.

Current analysis indicates collisions between orbital objects could potentially lead to a sustained growth in the debris population in select orbits and that debris mitigation alone will not be sufficient to prevent this increase.

¹ This could soon change since the recently (June 28, 2010) released National Space Policy directs NASA and the DoD to pursue research and development of technologies and techniques to remove on-orbit debris.

The goal of DARPA's Catcher's Mitt study was to model the debris problem and its future growth, determine where the greatest problem will be for U.S. assets and then, if appropriate, explore technically and economically feasible solutions for debris removal. Data and input for this study was gathered in four ways:

1. A series of U.S. Government roundtable meetings where operational space components of the U.S. Government shared their views of the problem, including how debris may affect their functioning assets, and discussed current debris-related activities;
2. An international conference, co-hosted by the National Aeronautics and Space Administration (NASA), on orbital debris removal held in December 2009;
3. Several utility studies conducted by NASA, RAND, Johns Hopkins University Applied Physics Laboratory (JHU APL), and Aerospace Corporation;
4. A Request for Information (RFI) where industry submitted concepts to solve subsets of the debris problem.

The results of these four activities were used to better understand the issues involved and determine whether DARPA investment in a new program is warranted, and where and how to be most effective.

2.3 U.S. Government Roundtable Meetings

Three government roundtable meetings were held during the course of the Catcher's Mitt study with representatives from NASA, the National Reconnaissance Office, Air Force, and the National Security Space Office. During these meetings several questions were asked of the attending organizations to focus the discussion. The following three aspects of potential debris removal efforts dominated the meetings:

- **Object Size To Remove:** There were two competing lines of thought on the issue of what debris class should be the focus of an orbital debris removal technology development program. One perspective was that debris mitigation strategies are driven by the smallest debris to which satellites are vulnerable since these objects cannot be tracked and also have far greater flux. The opposing view was that although these objects probably do pose the greatest risk, in the long run it will be more effective to immediately address removal of large objects (e.g., derelict satellites) since over time these are the source of the more dangerous small debris later due to explosions and collisions. By the end of the session there was general consensus that it made the most sense to pursue the removal of large objects.
- **Altitude Regime to Address:** It was noted that the current collision hazard in GEO is less severe than in LEO since the actual debris flux is considerably smaller and the relative velocities are significantly lower. The risk posed to an operational satellite in a stable geopotential well (the location of greatest risk in a GEO orbit) is comparable to low levels of risk that would be found in LEO. However, satellite operators, both government and commercial, are most concerned about the region in which their assets are located. NASA and other agencies that rely on a variety of imaging, communications, earth science, and remote sensing satellites are primarily concerned with LEO, whereas the DoD cares about both LEO and GEO due to the wide range of satellites deployed in both regions. Primary commercial interests are in the GEO region due to communications, broadcast, and meteorological satellites stationed there.

- **Timelines Necessary:** Most agreed that a rapid response solution would be desirable since the orbital debris after a major debris-generating event tends to spread out quickly. If a solution were launched within a few hours then the debris could be cleared much more efficiently than if a response were launched later. It was generally agreed, however, that the requisite responsive breakup detection, cloud characterization, launch, and intercept/rendezvous capabilities have to be developed first before this could be a reasonable possibility. As a result, efforts were focusing on the systematic removal of large derelict objects such as spent rocket bodies and nonoperational payloads.

2.4 Orbital Debris Removal Conference

From December 8th through 10th, 2009, DARPA and NASA co-hosted the first International Conference on Orbital Debris Removal, which was held in Chantilly, VA. The conference was attended by over 275 individuals from 80 companies, 20 universities and 9 countries. Over 50 presentations were given by representatives from various government agencies, industry and academia.

Presentations included both technical and non-technical discussions. The conference began with a series of briefs intended to provide a general description of the orbital debris problem, including measurements of the current environment, modeling of the future environment, and the costs and risks imposed on satellite operations by orbital debris. Several presentations were then given that discussed approaches to the problem both architecturally and from a management perspective. These were followed by discussions of the numerous legal and economic issues related to orbital debris removal such as: spacecraft ownership and removing other nation's debris; liability for damages resulting from either collisions or removal operations; and economic incentives, both in the form of fees and rewards. In addition, policy issues were addressed, such as the potential weaponization of debris removal methods. Presentations were also given describing potential operational concepts for debris removal and how to maximize the efficiency of any debris removal system.

Technical presentations given during the conference included several ideas that sought to take advantage of environmental forces such as atmospheric drag, solar radiation pressure, or the Earth's magnetic field. Lasers were also proposed as a possible debris removal method. A number of presentations suggested potential methods for capturing large objects through the use of nets, grapplers, or other devices. Proposals were also made for the use of specific spacecraft to deliver a debris removal system. Since the initial conference, at least two other countries have hosted conferences dedicated to the topic of orbital debris removal – one in Russia in April 2010 and another at the headquarters of the French National Space Agency (CNES) in Paris in June 2010².

2.5 Orbital Debris Studies

To better understand certain specific issues related to orbital debris removal, several detailed studies were chartered. The first of these was conducted by NASA's Orbital Debris Program Office to 1) evaluate the future debris population growth in the low Earth orbit (LEO) region under specified mitigation and removal scenarios, 2) demonstrate the effectiveness of the commonly-adopted mitigation measures and active debris removal, and 3) quantify the relative benefits of active debris removal in LEO to future space systems. Following the first U.S. Government roundtable, Aerospace Corporation was asked to help quantify the financial risk orbital debris poses to satellite operators. To accomplish this

² Weeden, Brian, "Saving Earth Orbit, One Piece of Junk at a Time", spacenews.com, August 2010.

Aerospace calculated the reduction to satellite lifetimes and the subsequent increase in the need for constellation replenishment resulting from collisions with debris for a variety of hypothetical but realistic constellations. Prior to reviewing the RFI responses received, JHU APL was commissioned to provide systems engineering parameters that would assist in the evaluation of those responses. Metrics such as required size, power and weight for theoretical debris removal systems were sought. RAND Corporation was tasked with performing a comparative analysis of prior environmental remediation efforts that have been conducted in the past that might shed light on potential timelines and trigger events for orbital debris removal. This study was intended to examine the potential political, social, and economic challenges that could be faced in pursuing an orbital debris removal program. The results of these studies are highlighted throughout this report.

2.6 Request For Information

The Request for Information (RFI) was written to encourage responders to consider both technical feasibility and economic efficiency when drafting their responses. While some of the over 80 RFI responses received contained a complete concept of operations, many focused on only one aspect of the orbital debris removal process, assuming the other aspects would be addressed in some acceptable manner. For example, some submittals addressed the issue of identifying which altitudes and inclinations should be targeted for debris removal efforts. Others provided information on spacecraft that could potentially deliver the debris removal solution developed. Still others focused on specific technologies such as grappling large derelict objects or despinning tumbling hardware. Responses were submitted from commercial industry, government labs, universities, and concerned citizens. These RFI responses provided significant insight into the state of technologies and theories related to orbital debris removal.

3 Understanding the Problem

3.1 Debris Environment

A number of recent high profile events have demonstrated the need to manage the growth of the orbital debris population. On February 11, 2009 an active Iridium satellite collided with a retired Russian satellite, creating over 1500 pieces of orbital debris large enough to be tracked from the ground. Just one month later, on March 12, 2009, the crew of the International Space Station temporarily evacuated to the Soyuz capsule in response to an anticipated near miss with a piece of debris. The growing risk of orbital debris is highlighted by the almost 100 collision avoidance maneuvers³ have been performed to date, with most taking place since 2008. It should be noted that the rise in the number of collisions and close encounters is consistent with increases in the total amount of orbital debris. There are over 15,000 objects tracked and cataloged in Earth orbit; each one large enough to cause catastrophic damage if it collides with any other space asset. Fifteen years ago only about half this number existed.⁴ Figure 1 shows the growth of the orbital debris population in LEO where approximately 80% of the cataloged objects reside.

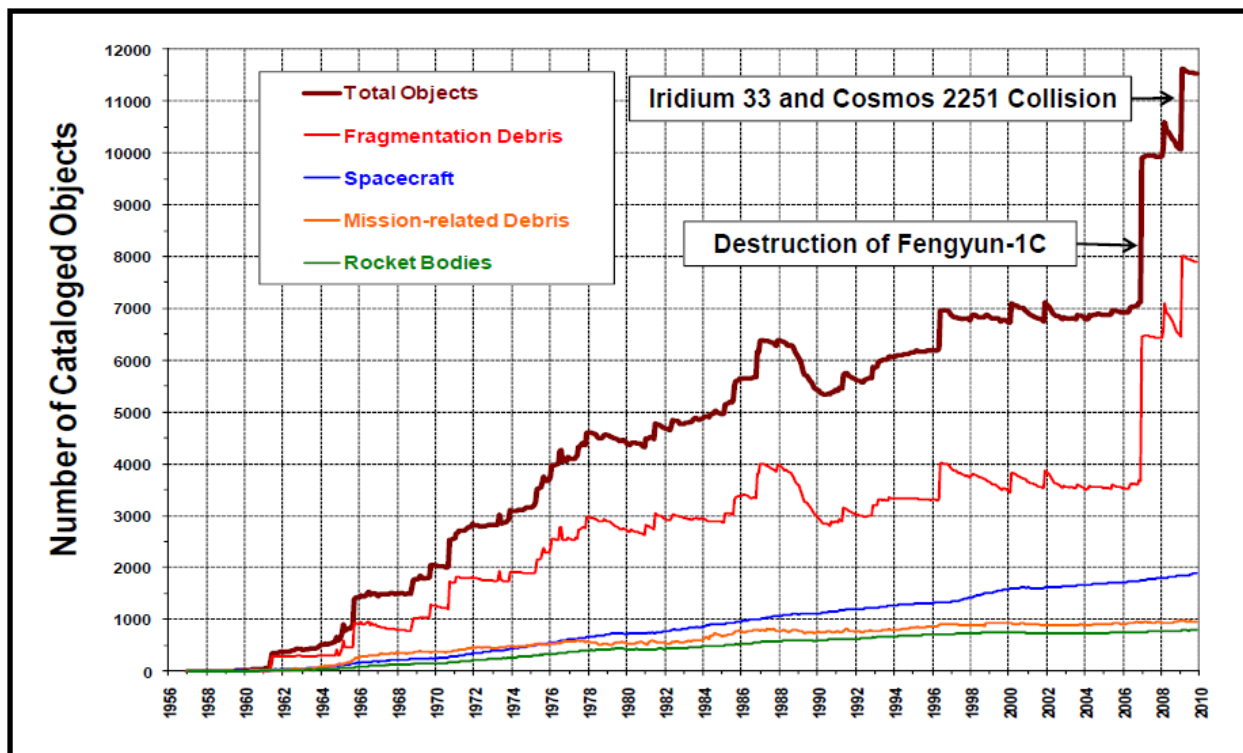


Figure 1 – Growth of the cataloged LEO space object population shows a large increase since 2007 due largely to two significant events.⁵

³ Ongoing technical discussions with Nicholas Johnson (NASA/JSC) and satellite operators from 2008 to present.

⁴ NASA Orbital Debris Quarterly News, vol. 14 issue 1, p 12, January 2010.

⁵ NASA Orbital Debris Quarterly News, vol. 14 issue 2, p. 4, April 2010.

The current collision hazard at geosynchronous (GEO) altitudes is small relative to the LEO environment (see Figure 2). As a result, the impetus to start active debris removal based on collision hazard will probably start in LEO. This observation could be altered if there are some major accidental breakup events or other unanticipated operational issues that arise in GEO. For example, the GEO region is much harder to access than LEO; many critical commercial and military payloads are being deployed in GEO; GEO satellites are generally larger and more expensive than LEO satellites; and there is no atmospheric drag to remove debris naturally.

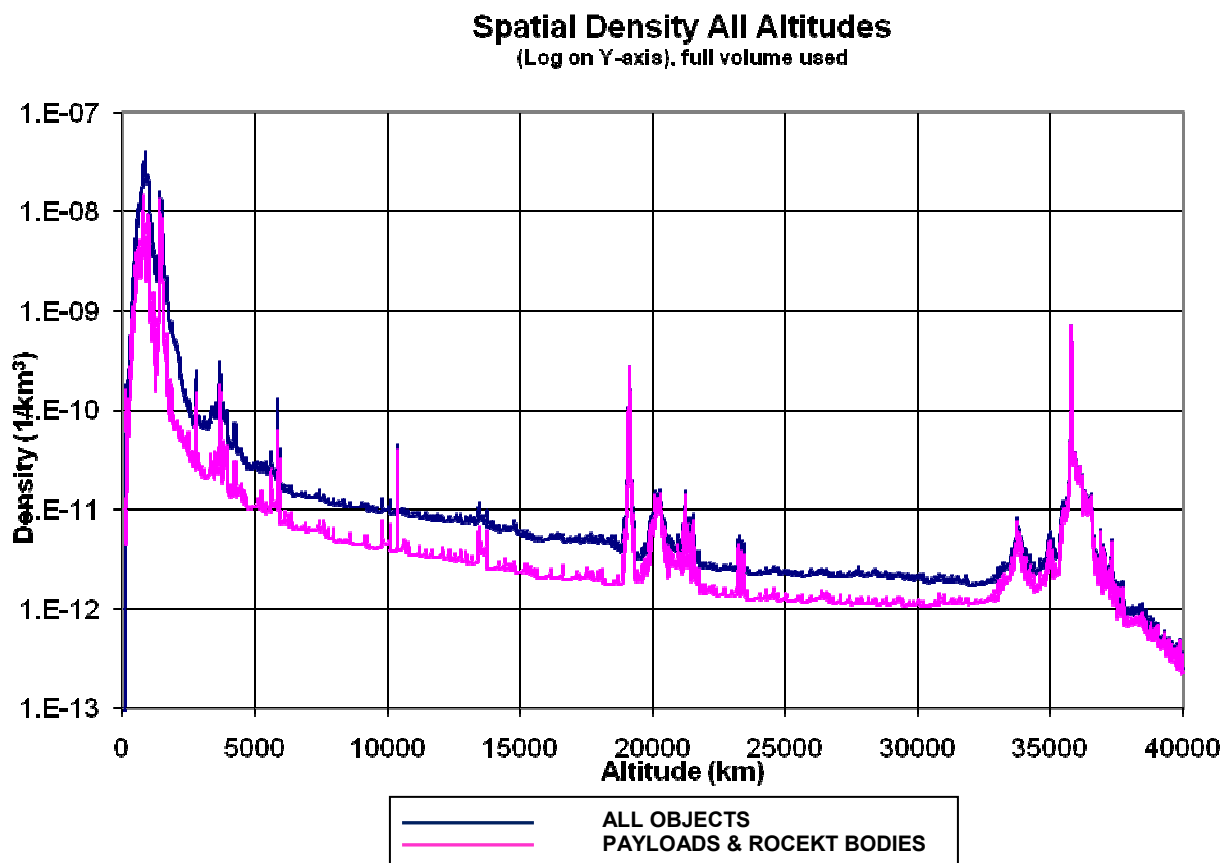


Figure 2 – The spatial density of cataloged debris shows highest levels in LEO with secondary peaks at semi-synchronous orbit and GEO.⁶

Furthermore, because GEO objects have maximum inclination values of only 15° and their orbital velocity is smaller, the relative velocities between operational satellites and derelict objects in GEO are likely to be much lower than would be the case in LEO. However, it is important to note that a major breakup event in GEO could potentially have far greater ramifications than one in LEO since the GEO band of operational satellites is so tightly constrained.

⁶ Nicholas Johnson, NASA Orbital Debris Program Office.

Broadly speaking, orbital debris can be grouped into three categories by size as shown in Table 3:

- **Small** - those that are too small to be either observed from the ground or cause significant damage (<5 mm).
- **Medium** - those that are large enough to cause significant damage (because they cannot be shielded against) and too small to be detected from the ground (5 mm – 10 cm).
- **Large** - those that are currently being tracked from the ground via the SSN (>10 cm) and will likely cause catastrophic damage upon impact.

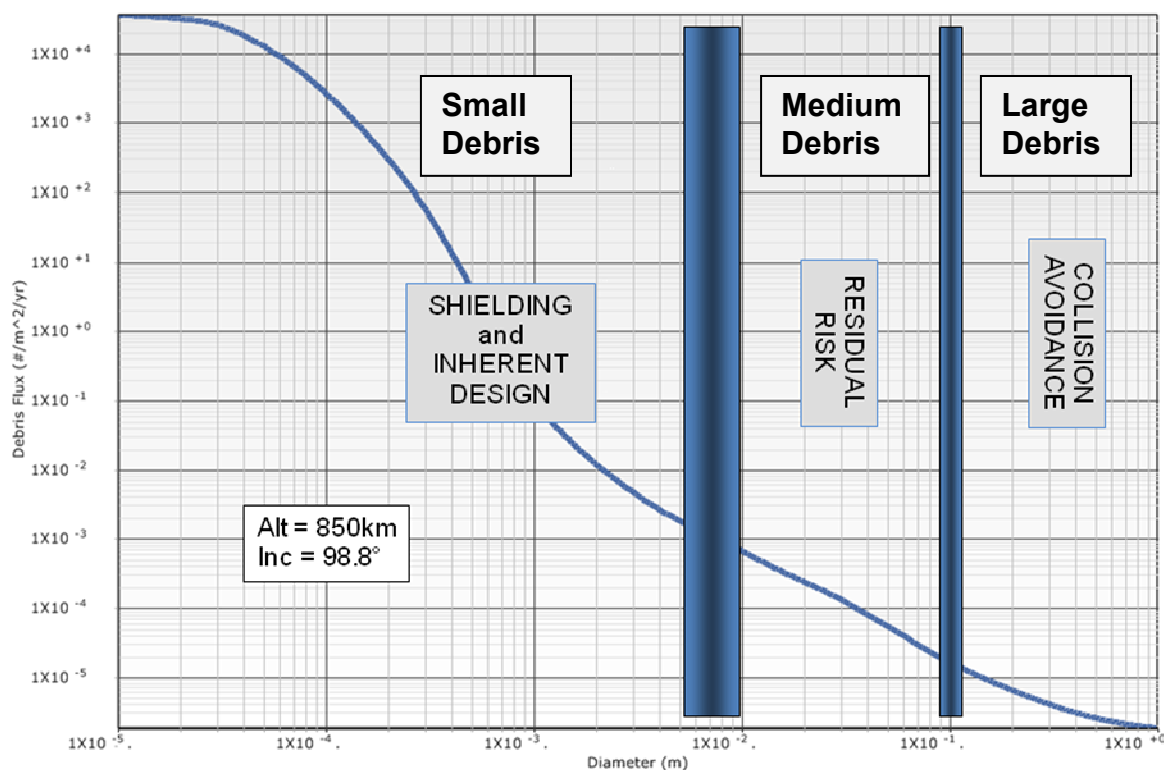


Figure 3 - The vast majority of debris can be either shielded against or avoided, but no countermeasure currently exists for medium (5 mm – 10 cm) debris.

Shielding and collision avoidance maneuvers are the primary means to protect operational spacecraft from debris. Current design practices generally allow spacecraft to survive impacts with debris of 5 mm or less. Providing collision avoidance information from the SSN to maneuverable spacecraft allows them to maneuver to avoid large debris, 10 cm and up. Armoring spacecraft to survive collisions with 5 mm to 10 cm sized medium debris is not economically feasible and is likely not technically feasible. Providing collision avoidance information to active spacecraft for the hundreds of thousands of these medium sized debris objects will only be of potential benefit to the subset of maneuverable spacecraft which can actually act upon that information. Even then, the information provided would have to be radically improved beyond current SSN capabilities to avoid unnecessary avoidance maneuvers, which would rapidly deplete spacecraft lifetime fuel reserves. Based on information⁷ from the Joint Space Operations Center (JSpOC), analysis conducted as part of this study indicates that if objects as small as 1 cm were tracked, the number of conjunctions evaluated by the JSpOC would increase from

⁷ C. Moss, "The Joint Space Operations Center and Orbital Debris", Dec. 2009.

approximately 75 each day to over 2,500. This medium debris, which is much more populous than the large debris (by a factor of 100) yet still capable of disabling or destroying spacecraft upon impact, is where most of the risk from orbital debris is posed. This medium debris is too large to be protected against with shielding and too small to be accurately tracked in order to be avoided – this is the population that is most important to be controlled in the future.

3.2 Future Environment

As was discussed in the previous section, the number of debris objects has doubled over the past fifteen years, and the number of objects is expected to continue growing into the future. Figure 4 displays the results of analysis conducted by NASA's Orbital Debris Program Office projecting the possible growth of the trackable debris population in three orbital regimes assuming no actions are taken to mitigate this growth. Although the Medium Earth Orbit (MEO) and GEO regions show nearly linear growth, the population of debris objects in LEO is projected to grow almost exponentially, with nearly five times as many objects 200 years into the future. This rapidly increasing growth rate is mostly due to the large number of collisions expected to take place in that region.

In an attempt to help control the future growth of orbital debris, most spacefaring nations have adopted measures to limit the creation of new orbital debris. In 1995 NASA was the first space agency in the world to issue a comprehensive set of orbital debris mitigation guidelines. Two years later, the U.S. Government developed a set of Orbital Debris Mitigation Standard Practices based on the NASA guidelines. Other countries and organizations, including Japan, France, Russia, and the European Space Agency (ESA), have followed suit with their own orbital debris mitigation guidelines. In 2002, after a multi-year effort, the Inter-Agency Space Debris Coordination Committee (IADC), comprised of the space agencies of 10 countries as well as ESA, adopted a consensus set of guidelines designed to mitigate the growth of the orbital debris population. In February 2007, the Scientific and Technical Subcommittee (STSC) of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) completed a multi-year work plan with the adoption of a consensus set of space debris mitigation guidelines very similar to the IADC guidelines. The guidelines were accepted by the COPUOS in June 2007 and endorsed by the United Nations in January 2008⁸. Currently accepted mitigation measures include limiting the use of explosive bolts and other disposable deployment mechanisms; limiting orbital lifetimes of retired payloads and spent rocket bodies to 25 years; and venting unused propellant at the end of operations. While the United Nations 2008 Report on Space Debris⁹ discusses these guidelines' contribution to a slower growth in the space debris population, these efforts have only slowed the overall growth in the amount of space debris, not halted it.

⁸ NASA Orbital Debris Program Office website, <http://orbitaldebris.jsc.nasa.gov/mitigate/mitigation.html>.

⁹ United Nations 2008 Report on Orbital Debris (A/RES/62/217).

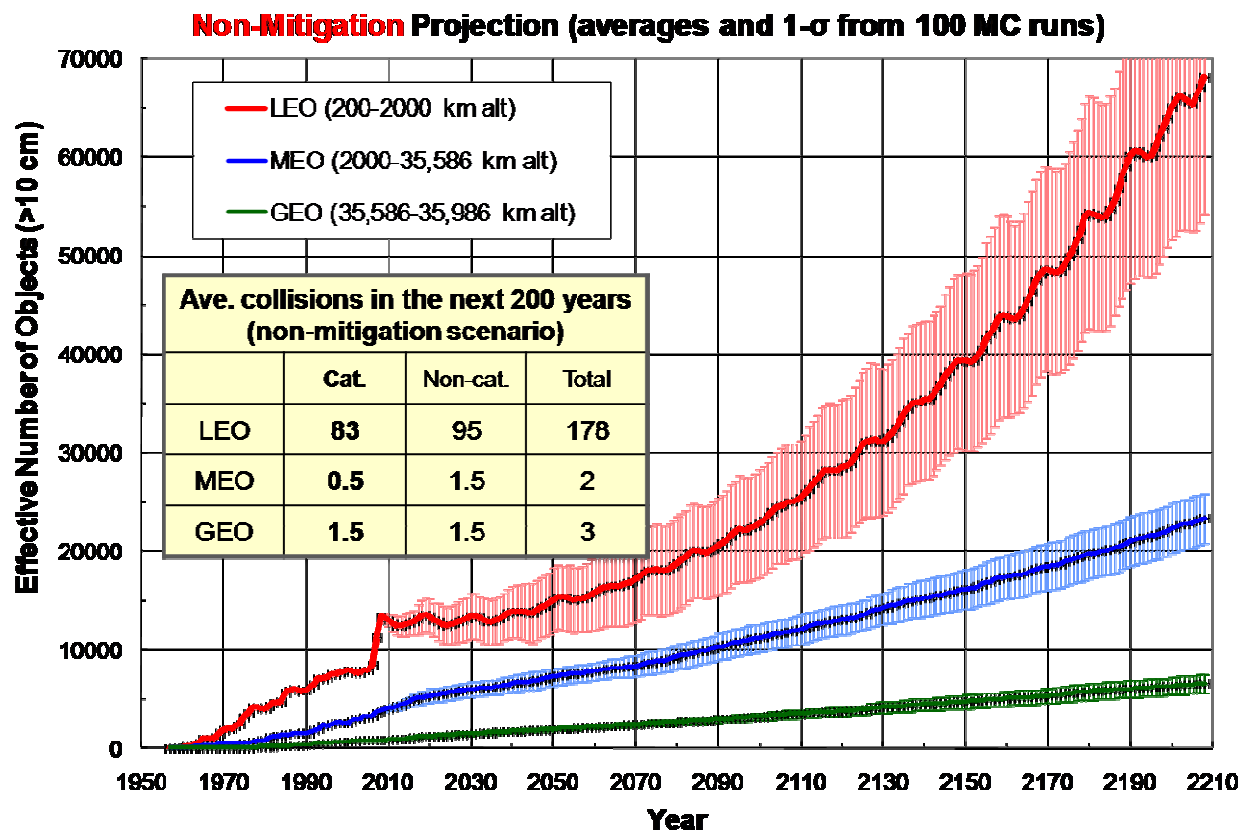


Figure 4 – If steps aren't taken to mitigate the creation of orbital debris, the debris population in LEO is expected to grow significantly over the next two centuries due to a large number of on-orbit collisions¹⁰.

To date, on-orbit explosions have been the primary source of debris. Nevertheless, collisions are expected to be the leading source within the next few decades. As shown in Figure 5, analyses conducted by NASA's Orbital Debris Program Office indicate that even in the absence of additional launches, the amount of orbital debris will continue to rise due to cascading accidental collisions. NASA estimates that collisions with operational spacecraft will occur approximately once every five years with the current population and with increased frequency as the debris population continues to grow¹¹.

¹⁰ J.-C. Liou, et al. A Review of the Recent NASA Long-Term Orbital Debris Environment Projection and Active Debris Removal Modeling Activities, p4, NASA-DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 8-10 Dec 2009.

¹¹ Nicholas Johnson in Space News, p18, May 10, 2010.

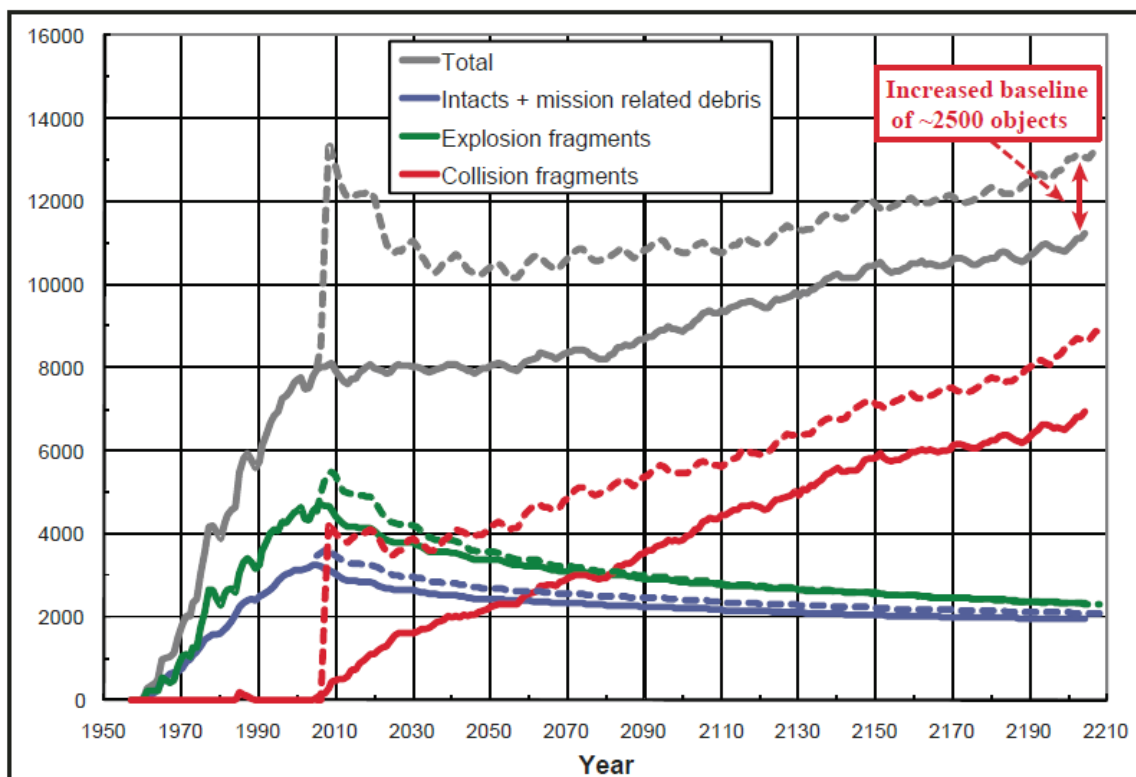


Figure 5 – Analysis by NASA demonstrates that the primary source of debris in coming years will be on-orbit collisions. The solid curves are a 200-year projection with no future launches beyond 2006. The dashed curves take into account the Fengyun-1C event and Iridium 33/Cosmos 2251 collision, which will contribute about 2,500 objects to the environment over time¹².

Figure 5 also demonstrates that models of the future debris environment are highly sensitive, and individual events can significantly alter the overall outcome. The two events cited in the figure significantly increased not only the near-term debris population, but the long term population as well.

3.3 Economic Analysis

On-orbit collisions have the potential for reducing the operational effectiveness or lifetime of active satellites by presenting an increased hazard to them, translating into potential lost capability and a financial cost to restore that capability. The Aerospace Corporation conducted a study¹³ in support of Catcher's Mitt to assess the impact of orbital debris on the lifetime and cost of a range of hypothetical constellations and satellite types. The orbital debris hazard faced by three hypothetical satellite constellations in sun-synchronous orbit was analyzed: a small constellation (5 satellites) of government weather satellites with a lifetime of about 6 years; a medium-sized (20 satellites) constellation of commercial Earth imaging satellites with a lifetime of about 9 years; and a large constellation (70

¹² J.-C. Liou, et al. A Review of the Recent NASA Long-Term Orbital Debris Environment Projection and Active Debris Removal Modeling Activities, NASA-DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 8-10 Dec 2009, p. 7.

¹³ W. Ailor, J. Womack, N. Lao, G. Peterson, and E. Murrell, "Effect of Space Debris on the Cost of Space Operations," Aerospace Corporation, TOR-2010(1106)-9938e, May 2010.

satellites) of commercial communications satellites with a lifetime of about 12 years. This study employed a Monte Carlo simulation to model the vulnerability of these satellites to impacts from various sized debris based on Computer-Aided Design (CAD) models. Critical components such as mission payloads, fuel tanks, and batteries were identified and the total cross-sectional areas of these components, as well as the surface area of solar panels, were calculated. The probability that debris of a certain size would cause the failure of a critical component was estimated based on this information. In addition, the reliability of each satellite was modeled using a combination of Weibull and Normal distributions to represent bus component reliability while impacts to the solar arrays were modeled using a Poisson distribution. The failure rates for each type of satellite were used to determine the increase in replenishment costs due to debris impacts.

Constellation/ Satellite Type	Mean Lifetime (No Debris)	Mean Lifetime & Percent Reduction (With Fatal Impacts Only) 2010-2040	Mean Lifetime & Percent Reduction (All Impacts) 2010-2040
Small/ Government	5.7 years	5.5 – 5.6 years 2.3-2.1%	5.4 – 5.5 years 4.4-3.4%
Medium/ Commercial	9 years	8.5 – 8.6 years 5.0-4.6%	8.2 – 8.3 years 8.9-7.6%
Large/ Commercial	12 years	11.5 – 11.6 years 5.7-5.1%	10.6 – 11.2 years 13.1-8.3%

Figure 6 - The mean lifetime reduction due to debris impacts for the constellation and satellite types ranges from 3.4 - 13.1%¹⁴.

From the results of this analysis it was shown that the probability of a fatal collision during the operational life of a satellite ranged from 4-8%. In addition, the mean lifetime of each satellite in the constellation was reduced between 3.4% and 13.1% within the 2010-2040 timeframe due to impacts with orbital debris leading to a corresponding increase of between \$700M and \$1.2B in constellation replenishment costs for these hypothetical constellations. While hypothetical, these results highlight the potential effects on future operational constellations and the critical attributes that will drive the costs imposed by future debris environments on operational satellites.

Constellation Size	Replenishment Cost (\$B, No Debris)	Replenishment Cost (\$B, Fatal Only)	Replenishment Cost (\$B, All Impacts)
Small	20.1	20.4 (2% increase)	20.8 (4% increase)
Medium	16.9	17.7 (5% increase)	18.4 (9% increase)
Large	7.9	8.6 (8% increase)	9.1 (15% increase)

Figure 7 - Increased satellite replenishment cost due to modeled debris impacts ranges from 4-15% of the total constellation cost¹⁵.

¹⁴ W. Ailor, J. Womack, N. Lao, G. Peterson, and E. Murrell, "Effect of Space Debris on the Cost of Space Operations," Aerospace Corporation, TOR-2010(1106)-9938e, May 2010.

3.4 Remediation Process

Orbital debris is not the first complex, multi-tiered problem faced by modern society. Other large problems, such as radon, spam, chlorofluorocarbons (CFCs), U.S. commercial airline security, acid rain, oil spills, asbestos, and U.S. border control have risk management processes found to be successful and are currently in a successful state of mitigation or remediation. To explore if the solution processes and risk mitigation steps used in these similar problems might shed light on the orbital debris challenge, RAND Corporation identified and analyzed the political, social, and economic challenges associated with these environmental and regulatory problems.

RAND Corporation outlined a framework (Figure 8) that demonstrates the steps of increasingly aggressive response to an issue that affects an entire community. The first step is to identify, characterize, and bound the problem. This step recognizes the problem and is a crucial step to allow the public to become aware of the inherent problem. In the case of orbital debris, the problem has been studied for a number of years within the community. The next progression in the framework is to establish an informal set the normative behavior. If this fails to address the problem these behaviors will likely be codified by a governance organization within the community, often including consequences for failure to comply. This is where the orbital debris problem resides today, with mitigation standards established as described in Section 3.1. The final step of the framework is to reverse the byproducts of the unwanted behavior through remediation. Again, for orbital debris this would mean removing debris that poses a hazard to operational spacecraft.

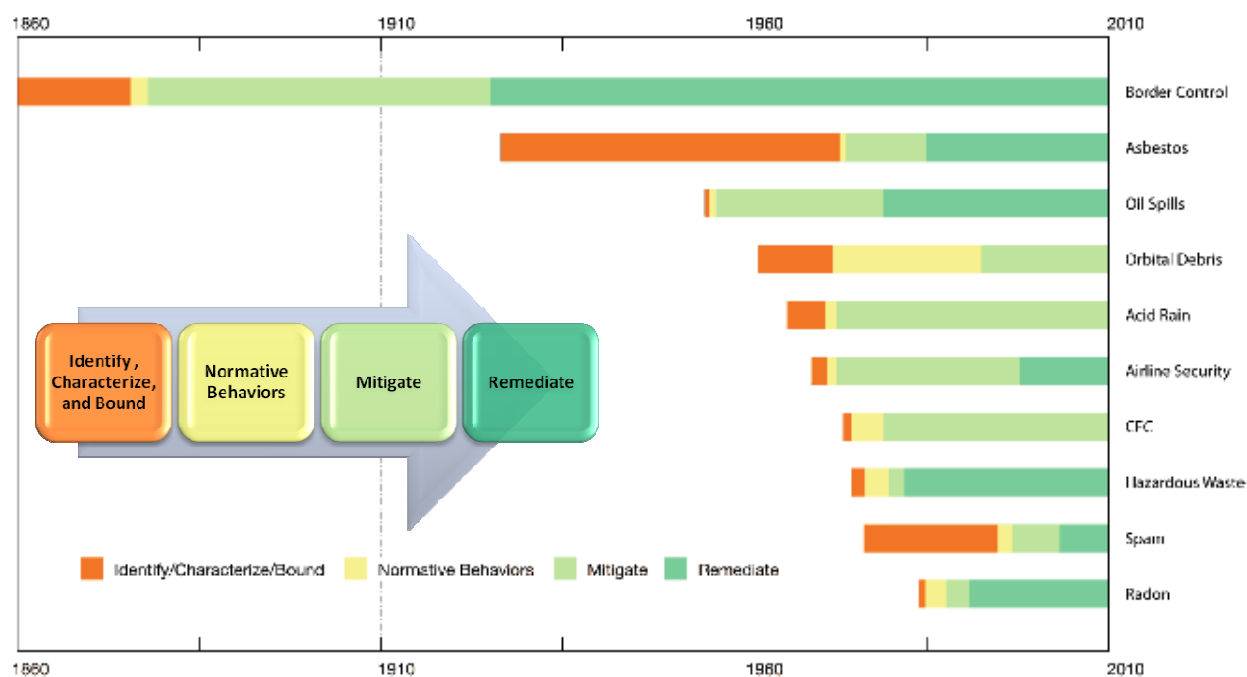


Figure 8 – The four steps of the environmental hazard framework provided by RAND for addressing a wide range of problems show that the timing and duration of each of these steps can vary greatly.

¹⁵ W. Ailor, J. Womack, N. Lao, G. Peterson, and E. Murrell, "Effect of Space Debris on the Cost of Space Operations," Aerospace Corporation, TOR-2010(1106)-9938e, May 2010.

The response of decision-makers to a specific incident is often times dependent on the community's perception and tolerance for the risk. A low tolerance for risk elicits a more rapid response through the four stage framework than a community with high risk tolerance. Frequently, a single critical event is enough to generate rapid movement through the four stages. This has not been the case for the orbital debris problem, despite the fact that the two most significant debris-generating events in history have occurred in the last three years. Despite the limited action, both within government and industry, it is clear that debris removal solutions will eventually be needed. The only question is how soon. It is possible that a solution won't be needed for several decades. However, there is also the possibility that a requirement to remove orbital debris will be thrust upon us relatively urgently as the result of one or more relatively unlikely, but highly significant, on-orbit events. For this reason an orbital debris removal system must be developed and tested as a contingency in case such an event occurs.

The 2010 Deepwater Horizon oil spill exemplifies the need for readily available mitigation and remediation methods. In the case of the Deepwater Horizon oil spill, a remedy was available to stop an oil leak at relatively shallow ocean depths. It was assumed that these techniques could be effective at greater ocean depths, but were never tested. Once the oil spill began it was quickly realized that the techniques used for shallow depth oil spills were not effective, leaving officials scrambling for a solution. Not only do officials need a means to remedy the situation, they also need to know that the particular technique works and it can evolve to meet future challenges. A similar situation could occur with orbital debris. If a significant event happens in orbit and decision-makers are not properly prepared to remedy the situation it could grow into a catastrophic event. The longer the community waits to address the problem, the higher the remediation costs will be.

4 Scenarios

Determining the appropriate response to the current debris situation will depend on the future circumstances that will be faced. Will the debris population continue to grow steadily as it has in the past, or will there be a sudden explosion in the number of debris objects possibly brought on by a space war? Will the decision be made to begin debris removal in LEO or GEO? Will technologies and concepts of operations be developed that will facilitate the removal of objects from a debris cloud following a breakup event before it has time to dissipate? Each of these different scenarios may have a unique solution or set of solutions.

The Catcher's Mitt study considered three potential scenarios when examining possible debris removal solutions: stabilizing the environment, recovering from a space conflict, and responding to a significant event.

- **Stabilizing the environment** calls for the active removal of debris objects within the normal predicted evolution of debris population. This rate of debris generation would allow for either the slow steady removal of debris as it is created or the removal of large objects before they breakup into medium-sized debris.
- The second scenario, **recovering from a space conflict**, examines debris removal methods appropriate for use during a war in which numerous spacecraft are destroyed on-orbit, rapidly increasing the debris population. This scenario calls for the expeditious removal of large amounts of debris either from specific orbital regions or throughout Earth orbit.
- The final scenario, **responding to a significant event**, seeks to quickly respond to individual events as they occur, such as removing debris fragments resulting from an on-orbit breakup, collision, or ASAT event. The intent is to capture and remove the debris while it is still relative concentrated. Another possibility would be to capture and remove a derelict satellite drifting along the GEO belt, threatening to collide or interfere with active satellites in its path.

Identifying the likelihood and consequences of each of these scenarios, as well as understanding which debris removal concepts work best in each, will assist in the selection of the most appropriate orbital debris removal method. Clearly it would be advantageous to select a method that would be effective in multiple scenarios. Determining which scenario is most appropriate involves answering several questions such as what technologies are available for each, how effective is each method at reducing the future medium debris population, and what are the costs and risks involved.

4.1 *Stabilizing the Environment*

Ideally time will allow the space community, both government and industry, to work toward an efficient cost effective solution for the removal of orbital debris. Once implemented, this solution need only keep pace with the creation of debris from collisions and other breakup events to maintain the current level of acceptable risk. Methods might target derelict satellites and rocket bodies for removal before they breakup, or concentrate on removing the most hazardous objects—medium-sized debris.

To demonstrate the effectiveness of mitigation measures and quantify the benefits of active debris removal, NASA conducted a study¹⁶ in support of Catcher's Mitt that evaluated the future growth in the LEO region under specific mitigation scenarios. LEGEND, a high fidelity 3-D model developed by NASA's Orbital Debris Program Office, was used to simulate the future debris environment. Figure 9 shows the results of this analysis for the population of debris objects 5 mm and larger. As can be seen from the figure, the debris population is predicted to more than double in the next 100 years if launch systems and procedures do not conform to and spacecraft (both satellites and rocket bodies) are not properly disposed of in accordance with current mitigation guidelines. Significant improvement can be made if a 90% success rate can be achieved in post-mission disposal (PMD) efforts. This is significantly higher than the current rate of approximately 70-80%. However, even 90% compliance with PMD guidelines will not prevent the debris population from growing at an increasing rate. Therefore, only by actively removing debris mass from the environment can the current debris population be maintained. According to NASA's study, only improving post-mission disposal efforts to 90% in concert with an active debris removal (ADR) program in which approximately five of the largest debris objects are removed annually (i.e., PMD+ADR05) will stabilize the debris population at current levels. Objects were selected for removal in this study based on the product of their mass and probability of collision. Therefore, both the likelihood and consequences of a collision between large debris objects were taken into consideration.

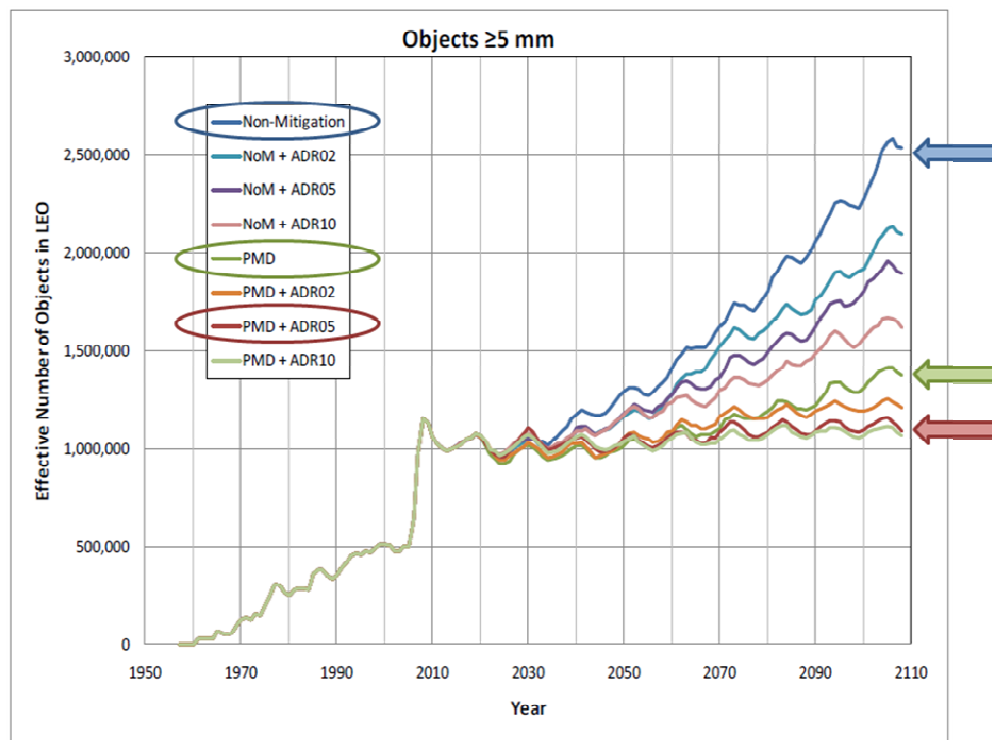


Figure 9 - Analysis conducted by NASA shows a significant reduction in the growth of the LEO debris population if post-mission disposal (PMD) mitigation guidelines are followed, but the debris population isn't stabilized unless five large debris objects are also removed each year (i.e., PMD+ADR05).

The PMD curve shown earlier in Figure 9 may prove to be optimistic because, as noted in Section 3.2, modeling the future debris environment can be highly sensitive to individual events. Figure 10 shows the range of likely values for the debris population given a 90% PMD compliance rate. Using the

¹⁶ Johnson, N. and Liou, J., "Active Debris Removal Scenarios – A Special Study for DARPA," September 2009.

mean+1 σ values it can be shown that the probability of collision with a medium-sized debris object will increase by 50% or more over the next one hundred years in much of the LEO region even with a 90% PMD compliance rate. If the higher values prove to be accurate, additional large objects will need to be removed to maintain the current debris population. Identifying the most efficient methods for removing large objects is discussed later in Section 5.1.

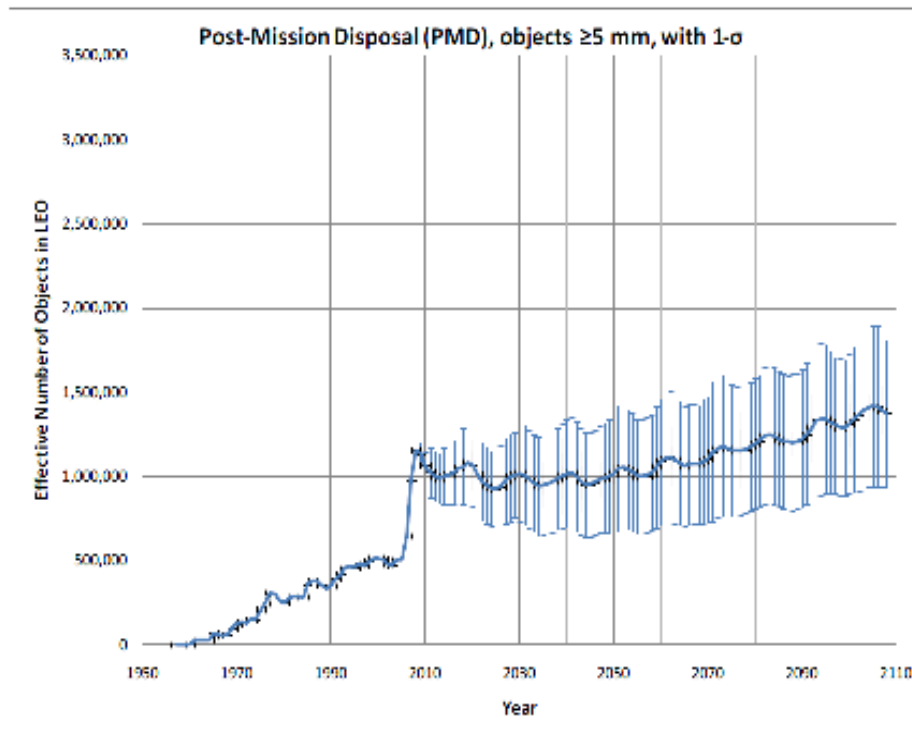


Figure 10 – Even if 90% of spacecraft were removed 25 years after mission completion, the population of medium debris will likely continue to grow.

An attempt to stabilize the debris environment in GEO would differ slightly from an effort focused on LEO. As was shown in Figure 2, the spatial density of debris in GEO is approximately two orders of magnitude less than in LEO. In addition, a careful examination of the figure will reveal that a larger percentage of the debris population in GEO is made up of large objects (payloads and rocket bodies). In addition, Figure 4 shows the projected debris population growth in GEO is much less than in LEO. Based on this information it seems that stabilizing the debris environment in GEO would be a less demanding task. In addition, removing large objects would likely be the preferred method. The efficacy of this method is further increased by the fact that 80% of the collision hazard in GEO is concentrated in only 15% of the objects (~150)¹⁷.

4.2 Recovering from a Space Conflict

This scenario envisions a situation in which the risk to spacecraft in certain regions of space has suddenly become prohibitively high due to the extremely high spatial density of debris objects. In effect,

¹⁷ D. Mcknight, J. Griesbach, and C. Rogers, GEO Object Characterization, AMOS Technical Conference, 31 Aug-1 Sep 2009.

the natural evolution of the debris environment has been artificially sped up and compressed. This situation would most likely be brought about by a conflict in which an adversary attacks several satellites of another nation in an attempt to reduce that country's reconnaissance, navigation or communications capabilities. The tens-of-thousands of debris objects resulting from such an attack could endanger operational U.S. satellites or prevent the reconstitution of U.S. satellite capabilities if it were the target of the attack. This would be a highly stressful scenario and would require prior planning, preparation, and a rapid response. Technologies applicable for this situation would focus on removing the large population of medium to large objects (up to approximately 1 m). These methods would also have to be effective over a wide range of altitudes since an attack could be launched anywhere, including GEO. Due to the extreme conditions of this scenario, some debris removal methods might be used that would have been rejected for the environment stabilization scenario. These methods might include technologies that pose a high risk to operational satellites. The need to quickly restore the environment may justify putting additional assets at risk.

4.3 Responding to a Significant Event

When attempting to stabilize the debris environment, the goal is to remove enough debris each year to prevent an overall increase in the number of debris objects. An alternative strategy would be to respond to individual breakup events as they happen. The concept would be to influence a debris cloud before it has time to disperse. Immediately following a breakup event the resulting cloud of debris is still tightly packed and more easily eliminated from orbit—if a response can be prepared quickly enough. However, this would be quite challenging because it would require the ability to detect and characterize the breakup, deploy the debris removal system, and intercept the debris cloud at a precisely determined location all within a short period of time. This would be demanding in GEO but even more stressing for LEO.

Another significant event for which a response might be launched would be loss of navigational control of a geostationary satellite. Such a spacecraft would begin to drift along the geostationary arc, potentially endangering or interfering with numerous operational satellites. Technologies and concepts used to respond to this event would be very similar, if not identical, to those used to remove large objects under the stabilizing the environment scenario. Therefore, the remainder of this section will focus on responding to a breakup event.

Rapid reaction is crucial when responding to a breakup event. As will be shown, debris clouds disperse quickly. As shown at the bottom of Figure 11, several steps must be taken to launch an effective response following a breakup event. Delays in simply detecting the event may prevent an effective response. Once detected, the breakup must be characterized and understood. This analysis must include, at a minimum, the orbital characteristics of the original object and the location of the breakup to calculate the appropriate response trajectories and geometries. Assuming a space-based or ballistic method is used, one or several launch vehicles must be prepared, and launch authorization received from cognizant authorities. Only then can debris removal operations begin. Two potential response timelines are shown below: the Rapid Capability does not currently exist (including for example an air-launched response) while the Optimistic Timeline is the best that we could expect to field in the current operational environment.

Breakup Event Timeline

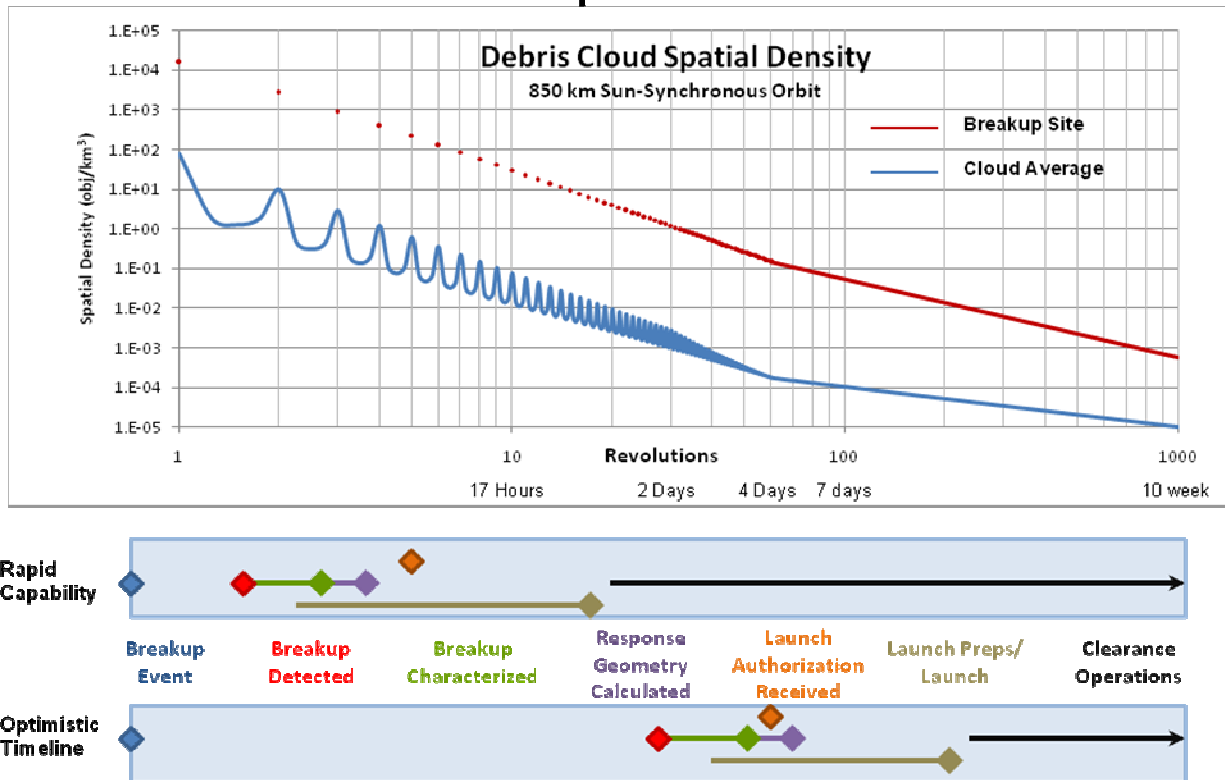


Figure 11 - In LEO a response will need to be launched within hours to take advantage of the higher debris spatial density following a breakup event.

Cloud Dispersion

During a breakup event, each resulting debris object retains the momentum of the original resident space object. In addition, each new debris object will receive an impulse, which is imparted as a result of the energy released from the breakup, varying both in direction and magnitude often inversely proportional to the fragment's size. No matter in what direction the debris is ejected, their resulting motion, short-term and long-term, is best described by examining the effects of the change in velocity in three orthogonal directions relative to the satellite reference frame:

- (1) Debris ejected along the velocity vector (i.e. in-track) have the altitude of their orbit changed preferentially. If ejected in the posigrade direction (i.e. along the velocity vector) the breakup point becomes the perigee and the impulse all goes into raising the apogee of the orbit. Similarly, for debris with a retrograde impulse (i.e. opposite of the velocity vector) the breakup altitude is now the object's apogee and the magnitude of the retrograde impulse drives the perigee of the fragment's orbit.
- (2) Debris ejected in the radial direction (i.e. straight toward or away from the Earth) primarily changes the eccentricity of the fragment's orbit. The resulting orbit has both a different apogee and perigee from the parent satellite but has no net increase in the semi-major axis (i.e. energy of the orbit).
- (3) Debris ejected perpendicular to the orbital plane (i.e. cross-track) changes the inclination and/or right ascension of the ascending node (RAAN) of the orbit. This perturbation does not change the

energy of the orbit, just its orientation relative to the Earth. A debris object receiving a cross-track impulse will deviate from the original orbit roughly the same distance as one receiving a radial impulse, only in a perpendicular direction.

In reality, it is likely that every fragment will have some impulse in each of these three directions, but the motion of the cloud is described well by looking at the cloud's extrema based on the effects of debris released in the three orthogonal directions. The internal characteristics of the cloud are determined by the fairly random distribution of impulses while the cloud edges are based upon the impulses provided in each of the three orthogonal directions alone.

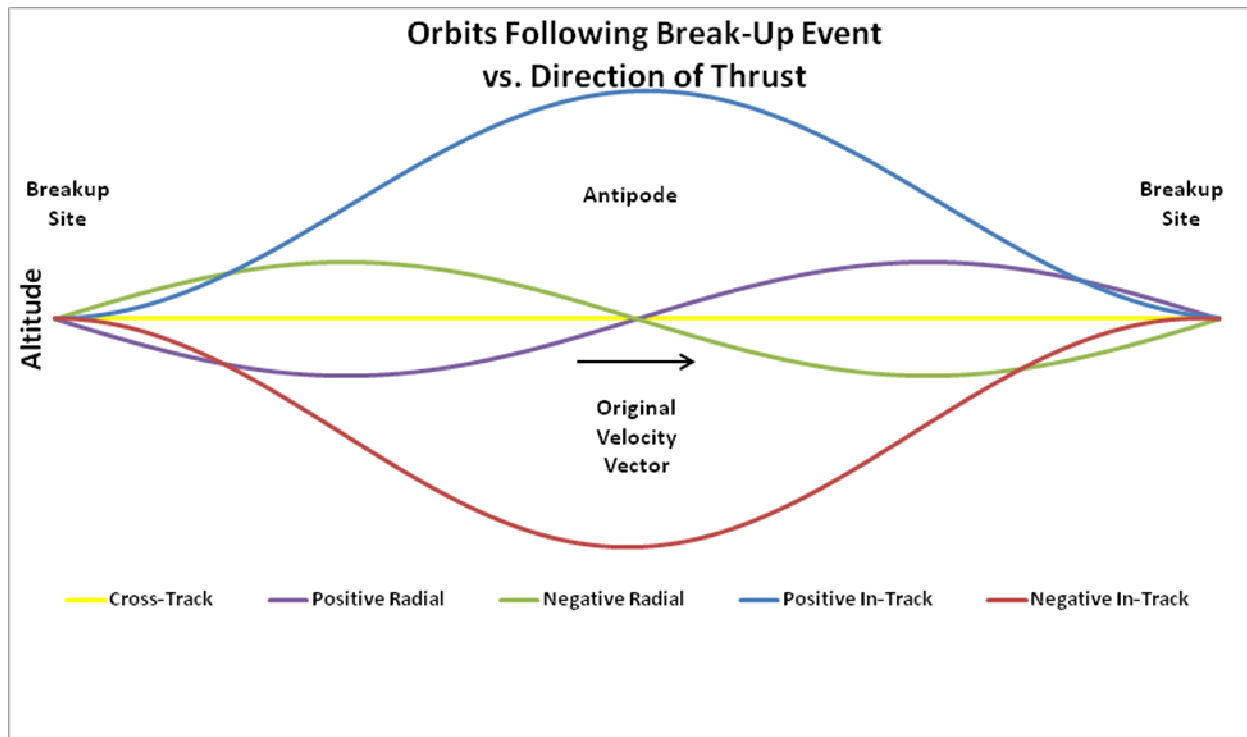


Figure 12 - Just like the other orbital elements, the altitude of debris objects produced from a breakup event will vary based on the size and direction of impulse received.

As can be seen from Figure 12, the cross-sectional area of the debris cloud will vary greatly from the point of impact to its antipode at the opposite side of the Earth. Because the debris passes through a narrower cross-sectional area at the breakup site, the spatial density of the debris increases at this point in inertial space. This causes a cyclical variation in the debris cloud spatial density as the cloud moves from impact site to antipode and back again, as shown by the blue line in Figure 11.

Within the debris cloud, variations in semi-major axis result in differences in orbital period and velocity. As a result, faster moving objects (those with lower perigees) outpace slower ones (those with higher apogees). Within a few hours or days the cloud stretches into a torus as shown in Figure 13. The growing size of the cloud as it assumes this shape is one reason for the downward secular trend in the cloud's spatial density. Once the cloud has completely encircled the Earth, the average spatial density within the cloud will no longer have a cyclical variation, although it will differ from one point to another, remaining highest in the vicinity of the breakup site.

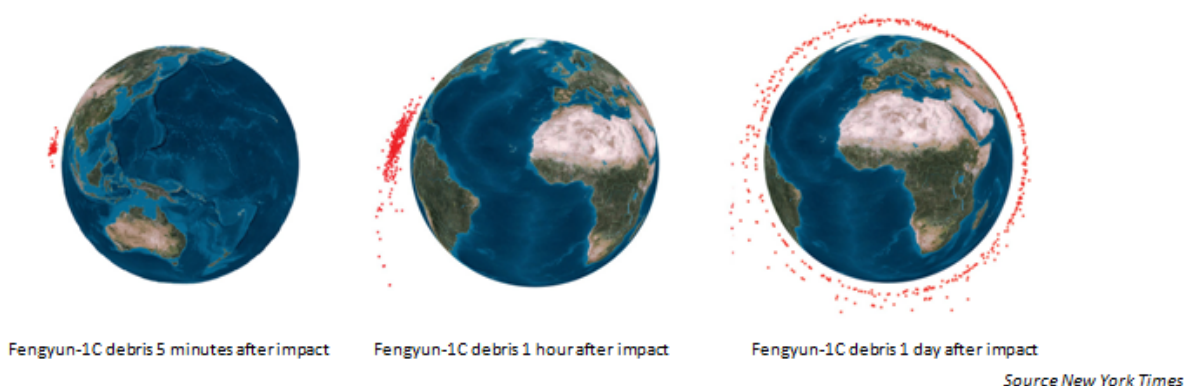
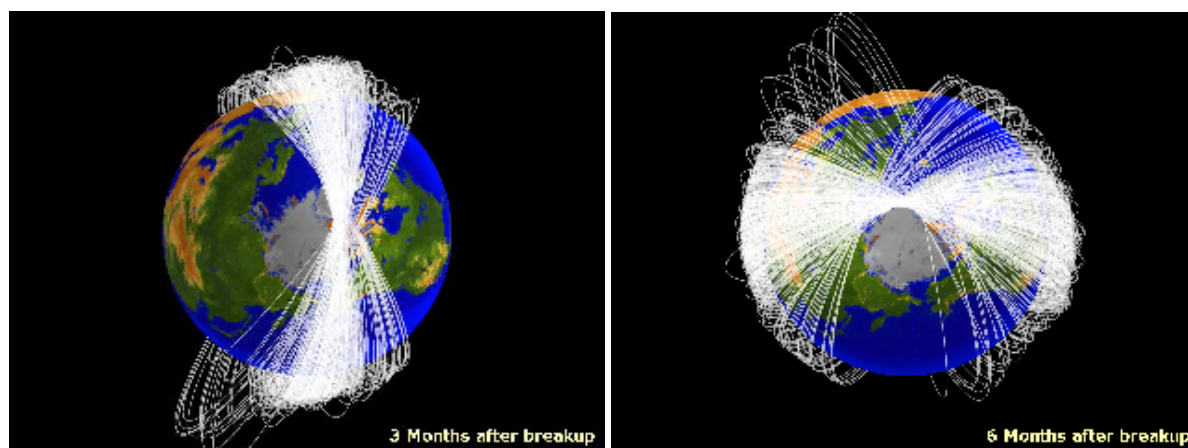


Figure 13 – Following a breakup event the debris quickly forms a ring around the Earth due to differences in orbital velocity between the debris objects.

In addition to the dismantling of the cloud due to variations in orbital period, variations in the inclination, eccentricity, and semi-major axis within the debris cloud result in the RAAN of the debris objects precessing at different rates. This causes the orbits of the various debris objects to slowly fan out, eventually forming a truncated sphere around the Earth after several months or years as shown in Figure 14. This is why the spatial density of the debris cloud continues to decline as shown in Figure 11, even after the cloud has stretched into a torus.

To complicate matters, the point at which the debris concentrates does not remain fixed. The right ascension of this point will continue to precess at the same rate as the original source object's ascending node. In addition, the argument of perigee of the debris objects will also precess due to the same perturbations. Therefore, the point where the debris concentrates slowly moves around the orbit, causing both the right ascension and declination of the breakup site to change over time.



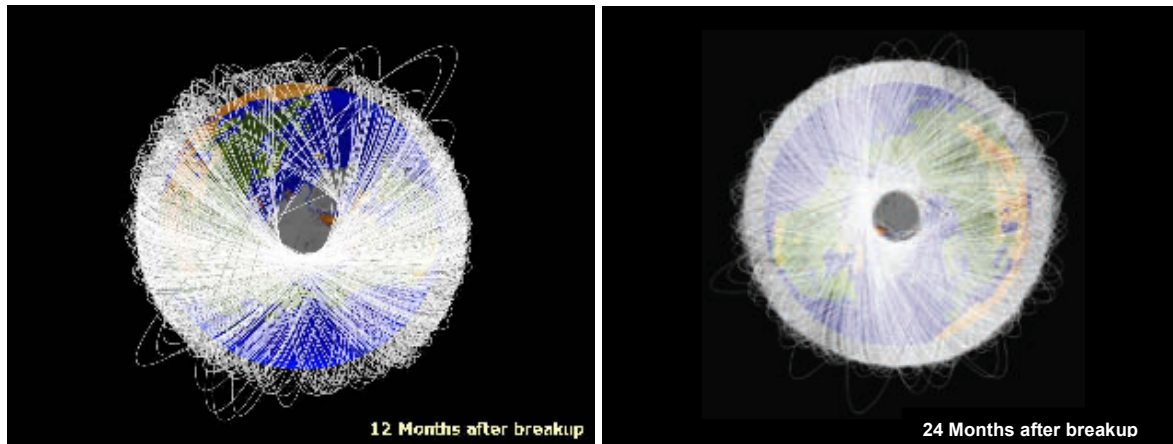


Figure 14 - After several months to a few years, the debris forms a truncated sphere around the Earth.

Geostationary Orbit

As was mentioned at the beginning of this section, two types of events could take place in GEO that require a response: a spacecraft breakup, or the loss of control of a satellite. Because removing an intact satellite is precisely what is done in the stabilizing the environment scenario this section will only discuss responding to a breakup event.

The debris cloud following a breakup in GEO would evolve somewhat differently than in LEO. Because relative velocities are much lower in GEO fewer objects would result from a collision, and the impulse imparted on each debris object would be considerably less. However, even a small impulse can significantly alter an object's orbital characteristics at geostationary altitude. In LEO 50 m/s will change an object's inclination by 0.4 degrees or increase its apogee by 200 km. In GEO the same delta-V will result in a 1.0 degree change in inclination or a 3,000 km increase in apogee. Also, because objects in GEO are normally placed in very low inclinations, the resulting debris cloud will eventually form a belt around the Earth near the equatorial plane rather than a truncated sphere. This could prove to be a big advantage in GEO: the orbital plane of the debris objects will not precess significantly over time. In addition, unlike LEO where the debris encircles the Earth in a day or two, in GEO it would likely take months. Yet, this relatively slow expansion of the debris cloud still results in debris being dispersed over large distances. A delta-V of only 1.0 m/s will cause the debris cloud to stretch an additional 500 km along the GEO belt each day.

Summary

The capability to respond to a significant event could provide the ability to rapidly remove medium-sized debris objects immediately following an on-orbit breakup. This capability could potentially be used in concert with an attempt to stabilize the environment since collisions will still take place under that scenario. However, time is of the essence, especially in LEO. The debris will quickly disperse, making the task more difficult the longer it takes to execute.

5 Orbital Debris Removal Methods

The following subsections examine the debris removal methods put forth at the Debris Conference, as responses to the RFI, and in the open literature. The analysis of these methods was conducted to determine which of these concepts could be eliminated from consideration based on the application of the basic physics. For those methods that appear physically feasible, the necessary requirements for future development are addressed. Generous assumptions were made in the following analyses in order to provide a liberal assessment and to not eliminate any methods that have even a slight potential for success.

To establish a goal for these analyses two alternative methods were considered: either attempting to maintain the current population of medium-sized objects, or attempting to remove the number of objects resulting from the breakup of a single satellite. According to NASA's LEGEND model there are approximately 1,150,000 medium debris objects currently in LEO. This yields an average growth rate during the space age of roughly 23,000 objects each year. Analysis done in the 90's by Dr. Darren McKnight¹⁸ demonstrated that approximately 20,000 objects result from the catastrophic breakup of a 3000 kg satellite. For comparison purposes within this study, 20,000 objects was the common metric employed. This was done in part so the results of the medium object removal analyses could be compared to other methods proposed for removing large debris objects prior to their involvement in a collision.

Any system intended for removing orbital debris will generally include four stages during a debris encounter: 1) detection; 2) interception/rendezvous; 3) interaction; and 4) disposal. Although some systems examined in this study relied on happenstance encounters with debris over time, most actively targeted specific debris objects, and therefore detecting those objects was a necessary first step. Proposed methods of detection included both on-board and ground-based systems, including the SSN. Regardless of the detection method used, any debris removal system must interact with the debris by intercepting it, rendezvousing with it, or via an energy pulse or beam, imparting a force on the debris. Nearly every method examined used this interaction to relocate the debris either to a safe, unused orbit (e.g., a super-synchronous orbit for GEO) or to deorbit the debris back into the Earth's atmosphere. Only a few methods proposed other means of disposal, such as completely vaporizing the debris, breaking it up into sub-millimeter particles, or reusing it in some manner.

Because spacecraft can be designed to survive impacts of objects less than 5 mm, only methods to remove medium (5 mm to 10 cm) and large (greater than 10 cm) orbital debris are addressed in the sections below.

5.1 *Large Object Removal*

For large object removal there are two critical issues to be addressed: which objects should be removed first and what removal solutions should be used. Appendix C provides a detailed analysis of likely objects that should be removed from orbit to minimize the chances of significant collision events.

The methods examined below are for removing orbital debris larger than 10 cm, including intact inoperative spacecraft, rocket bodies, and upper stages. For several reasons the largest objects in this

¹⁸ McKnight, D., Maher R., and Nagl L., "Fragmentation Algorithms for Strategic and Theater Targets (FASTT) Empirical Breakup Model," DNA-TR-94-104, October 1994

category would generally be targeted for removal. The primary reason for this is efficiency. If the largest objects are removed more mass is eliminated per object, thereby potentially preventing the creation of a greater number of medium debris objects. In addition, the largest objects would be easiest to track and potentially easier to capture as well.

Most ideas examined in this section possess unique challenges not encountered when removing medium debris object. Large object removal generally employs advanced rendezvous and proximity (RPO) operations and sophisticated grappling techniques (other methods of capturing large objects were also proposed: net, inflatable longeron, tethered harpoon, articulated tether/lasso, and electrostatic/adhesive blanket). The significant challenge of grappling a large debris object is further complicated if the object is tumbling or has energetic materials onboard.

To better understand these issues an analysis¹⁹ was conducted by the Johns Hopkins University Applied Physics Laboratory (APL) in support of Catcher's Mitt. Their analysis identified angular momentum cancellation as a major impediment to large debris removal. Particularly, this presents a major issue for the removal of GEO satellites since many of these satellites were spin-stabilized and are likely to have large values of residual angular momentum. However, in LEO, most target objects have low values of angular momentum due to a combination of internal momentum devices, gravity gradient stabilization and aerodynamic torques. In order to evaluate the difficulty of reducing the angular momentum of a target piece of debris, APL analyzed a notional derelict GEO dual-spinning satellite. Based on its known moment of inertia and angular momentum, the amount of propellant required to de-spin this satellite was calculated to be only 0.36 kg assuming a modest specific impulse of 300 seconds.

APL also examined the potential use of an articulated arm similar to the ISS robotic arm to grapple debris objects, and the following operational issues were identified:

- Large debris objects may not have convenient grapple attach points;
- Grappling devices must function on almost any shape, object, or surface;
- Viable machine vision for grapple point ID, tracking and capture must be deployed; and,
- Attitude compensation for grapple arm motion must be taken into account.

However, the following positive attributes of articulated arm mechanisms were identified:

- Multi-link robotic arms are the most common and mature means to grapple for servicing satellites or ISS modules, and for docking and assembly; and
- Viable approaches exist for grappling cooperative and non-cooperative (including tumbling) debris in close proximity.

Another unique challenge for these systems is the large energy / delta-V / fuel requirement imposed. To maximize efficiency orbital debris removal systems must remove multiple objects each mission. Therefore, unlike most spacecraft, which only need to stationkeep during their mission life, orbital debris removal systems must not only maneuver between several debris objects, but also impart a delta-V on each object to deorbit or relocate it. For this reason, identifying clumps of massive debris objects in narrow altitude and inclination bands would be very useful to minimize the amount of maneuvering required between objects. Table 1 shows five such groupings. In this table several types of delta-V calculations are made:

¹⁹ Marshall H. Kaplan, Bradley Boone, Robert Brown, Thomas B. Criss, Edward W. Tunstel, Engineering Issues for All Major Modes of In Situ Space Debris Capture, AIAA-2010-8863, August 2010.

- Moving between each of these objects only using (i) two Hohmann transfers per maneuver and (ii) using a low thrust maneuver;
- Synchronize with each object by (iii) raising the apogee by 200 km and letting the object move underneath then returning to the circular orbit and (iv) executing a 10° plane change to synchronize with the next object.
- Move each object to a perigee of 500 km (i.e., move to orbit with orbital lifetime well under 25 years).

Making contact with each object is provided simplistically in Column A and the Column B values add the requirement to synchronize with the objects that are randomly distributed by right ascension and true anomaly. The sum of Columns A and B would be the likely delta-V required if a propulsive tug was used to attach an inflatable device, electrodynamic tether, etc. Column C is total if the propulsive tug used to rendezvous with each object is used to execute a “deorbit” maneuver.

Group	Altitude Range (km)	Inclination Range	Number	A. Move Between		B. Synchronize		C. Deorbit	Total	
				i	ii	iii	iv		v	vi
1	815-865	70.89-71.11°	40	0.039 km/s	0.050 km/s	2 km/s	50 km/s	3.6 km/s	6 km/s	54 km/s
2	750-900	81.08-81.28°	54	0.103 km/s	0.116 km/s	3.2 km/s	69 km/s	4.6 km/s	9 km/s	74 Km/s
3	1000-1500	82.47-82.56°	63	0.248 km/s	0.356 km/s	3.8 km/s	78 km/s	12 km/s	16 km/s	90 km/s
4	600-900	96.94-98.07°	31	0.394 km/s	0.193 km/s	1.8 km/s	39 km/s	1.8 km/s	4 km/s	41 km/s
5	700-1000	98.15-99.04°	54	0.270 km/s	0.231 km/s	3.2 km/s	69 km/s	5.0 km/s	9 km/s	74 km/s
Total #			242	1	0.95	14	305	27	44	333
Total Mass Removed			1E6 kg	km/s	km/s	km/s	km/s	km/s	km/s	km/s

Table 1 - There nearly 250 objects constitute about 1,000,000 km of mass - about 4% of all mass in orbit.

5.1.1 Propulsive Tugs

Solutions that attach or use an active thrust device (i.e., consume some onboard fuel source) to remove the debris fit within this category. In some concepts, a mothership with expendable deorbit devices is employed to mitigate the high fuel budgets this approach entails. Electric propulsion systems (ion thrusters) coupled with an advanced solar photo-voltaic power system are also an often discussed solution to the fuel challenge. Alternately, electrodynamic tethers, solar sails, and other concepts have been proposed as propellantless propulsive options. These solutions are described in Section 5.1.2 below and typically would be used to maneuver an orbital debris removal system between debris objects. Propulsive tug solutions align well with removal of large debris, including intact objects (inactive spacecraft, rocket bodies, and upper stages). These methods are applicable in both the LEO and GEO regions as noted below.

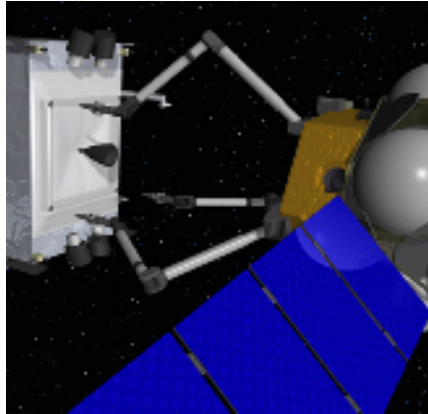


Figure 15: NRL-DARPA SUMO concept tug grappling a legacy spacecraft²⁰

5.1.2 Propellantless Solutions

Several methods have been suggested to relocate debris without expending onboard fuel. Most make use of natural forces found in the space environment to impart a force on the debris in order to relocate it. Environmental forces proposed included atmospheric drag, solar pressure, and the Earth's electromagnetic field. Other solutions attempt to transfer momentum from the debris removal device to the debris itself. Many solutions in this category could be used in a mothership configuration where the mothership would rendezvous with individual debris objects, attach a device to deorbit or relocate that object, and then move on to rendezvous with the next object. In this way time and fuel are conserved when moving from one object to the next. The various types of propellantless debris relocation methods are listed below.

- **Lasers:** Vaporize orbital debris or impart propulsive force via ablation. Applicable in LEO only. See Section 5.2.4 for details.
- **Drag Enhancement Devices:** There are devices, usually inflatable, with very high area to mass ratios intended to increase the atmospheric drag on a large debris object and expedite its reentry. Applicable to the lower regime of LEO only.

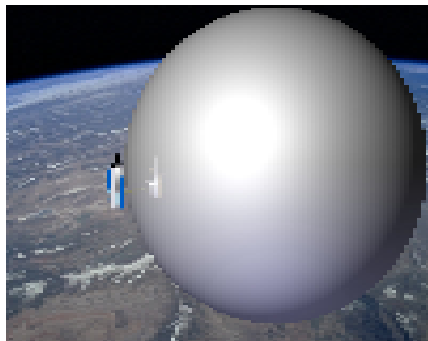


Figure 16: Drag enhancement device²¹

²⁰ Naval Research Laboratory, Space-based Solar Power: Possible Defense Applications and Opportunities for NRL Contributions, NRL/FR/7650--09-10,179, October 23, 2009, p75.

²¹ Global Aerospace Corp., Gossamer Orbit Lowering Device (GOLD), <http://www.gaerospace.com/projects/GOLD/index.html>, August 2010.

- **Solar Sails:** Solar sails rely on solar radiation pressure to provide thrust to a debris object in order to deorbit or relocate it. Solar radiation pressure is a dominant environmental force in GEO.

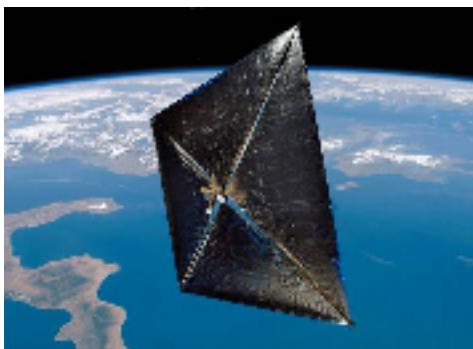


Figure 17: Solar sail²²

- **Electrodynamic Tethers:** A passive tether, generally several kilometers long, attached to a debris object in LEO, will build up an electric potential as it passes through the Earth's magnetic field. If electrons are expelled from one end of the tether, the resulting current will interact with the Earth's magnetic field creating a force that will slow the debris object, and cause it to deorbit more quickly. The plasma environment in LEO, which extends higher than atmospheric effects, is instrumental in facilitating the flow of electrons on the tether. Therefore electrodynamic tethers can be used at higher altitudes than drag enhancement devices (up to approximately 1,200 km). However, they become less effective at high inclinations. Survivability is a concern for tethers. The extremely thin material of the tether could easily be severed by debris. The use of multi-stand tethers with periodic connection points could help mitigate this problem, but would complicate deployment of the tether. To further complicate the use of tethers for orbit changing applications, long tethers exhibit certain libration modes that have been shown to be unstable. Therefore, any proposed tether system must include a stabilization solution.²³

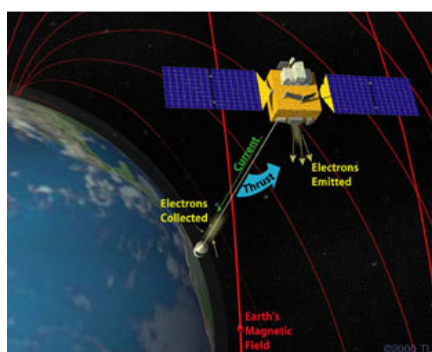


Figure 18: Electromagnetic tether²⁴

²² NASA Small Satellite Missions, http://www.nasa.gov/mission_pages/smallsats/10-109.html, August 2010.

²³ Marshall H. Kaplan, Bradley Boone, Robert Brown, Thomas B. Criss, Edward W. Tunstel, Engineering Issues for All Major Modes of In Situ Space Debris Capture, AIAA-2010-8863, August 2010.

²⁴ Tethers Unlimited, Electrodynamic Tethers, <http://www.tethers.com/EDTethers.html>, August 2010.

- **Momentum Tethers:** A momentum tether would be attached between a debris removal device and a debris object. The tether would be extended to several kilometers, and then cut or released. The resulting transfer of momentum from the combined system to the individual device and debris object, if timed properly, could increase the device's apogee and decrease the debris object's apogee, potentially reducing the debris object's orbital lifetime. An APL analysis for this report found that momentum tethers are problematic because of issues with guaranteeing their dynamic stability and the complexity of the control system required to manage them during proximity maneuvers. Momentum exchange tethers rely on the ability to capture an object during a high speed pass, i.e., grab it as the end of the tether swings by. This assumes a level of prediction and control that is currently beyond the state of the art. More research into methods of control and dynamics modeling needs to be completed to enable this technology for specific future mission applications.

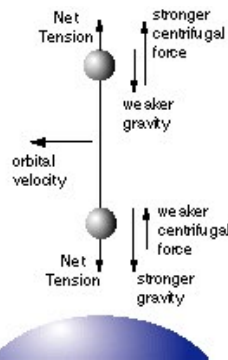


Figure 19: Momentum exchange tether²⁵

5.2 Medium Object Removal

The methods of orbital debris removal examined in the sections below are for debris from 5 mm to 10 cm in size, except where noted.

5.2.1 Sweepers

Those methods that rely on debris impacts to capture, retard, or breakup debris objects are classified as sweepers. Once deployed these systems would “sweep” out high-density orbits such as polar, sun-synchronous or geostationary orbits. These concepts generally involve the use of low density material or multi-layer shielding. In theory, the sweeper would capture the debris directly within its material structure, or sufficiently reduce the debris' velocity as it passes through the material so as to expedite the atmospheric re-entry of the debris object. Concepts of this class include the use of whipple shields, aerogel panels or structures, large multi-hulled spheres, and layered open-cell foam. Sweepers are intended for use against small and medium debris objects, and therefore are only appropriate for stabilizing the environment or responding to a significant event. The need for high numbers of interactions with debris objects greatly reduces their potential use in GEO. Therefore, they are generally proposed for use in LEO.

²⁵ Tethers Unlimited, Momentum Exchange Space Tethers, <http://www.tethers.com/MXTethers.html>, August 2010.

In order to speed up the response time of sweeper configurations and to avoid the larger objects that might destroy these passive systems, sweepers might be given proximity sensors and propulsion systems so they can be maneuvered towards debris that exist in specific orbits due to recent breakup events (such as the Fengyun-1C ASAT test). This approach could potentially clear out more debris with fewer spacecraft, but is considerably more complex than the passive sweeper concept. As with their passive counterparts, these active sweepers are intended for use in stabilizing the environment or responding to a significant event. Their ability to maneuver could create a potential application in GEO, particularly in response to an on-orbit breakup.

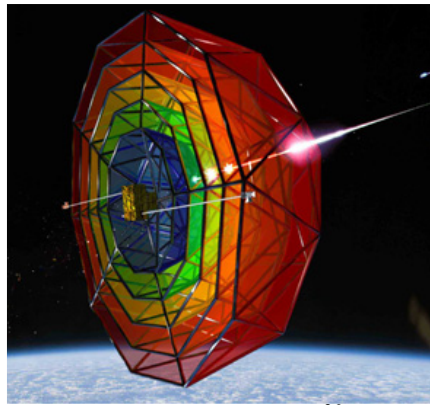


Figure 20: Sweeper²⁶

Passive Sweepers

An analysis was conducted to determine the number of passive sweepers needed to effectively control the medium debris population in LEO, and to identify the associated collision risk with large debris (>10 cm). To carry out this analysis, the debris flux for an 850 km sun-synchronous orbit was used. This orbit has one of the densest debris populations, and yields the most efficient results attainable for a passive sweeper. Results using flux levels for this orbit show that a debris collector with a cross-sectional area of 700 m² is needed to encounter an average of one medium debris object each year. Several proposed concepts have suggested using 10-20 m spheres as passive sweepers, which have a cross sectional area of 78 and 314 m², respectively. As shown by examining the blue diagonal line in Figure 21, which represents the number of encounters for 5 mm objects for a given sweeper size, a 20 m sphere (the purple dashed line) is not likely to encounter any medium debris objects during a year even in the densest debris regions. This conclusion was reinforced by analysis conducted by NASA Glenn Research Center²⁷. The NASA researchers concluded that four aerogel panels with a total area of 4,645 m² operating in the region between 740 and 1,020 km altitude for three months would encounter few, if any, centimeter-sized objects. In fact it would take over 45,000 twenty-meter spheres to remove 20,000 medium-sized objects per year.

²⁶ Space News, ATK Proposes Satellite To Fight Space Debris, <http://spacenews.com/civil/100809-atk-satellite-fight-space-debris.html>, August 2010.

²⁷ Meador, M. and Melis, M., "A Polymer Cross-Linked Aerogel Concept for Small Orbital Debris Removal in LEO", response to DARPA RFI on Orbital Debris Removal, DARPA-SN-09-68, December 2009.

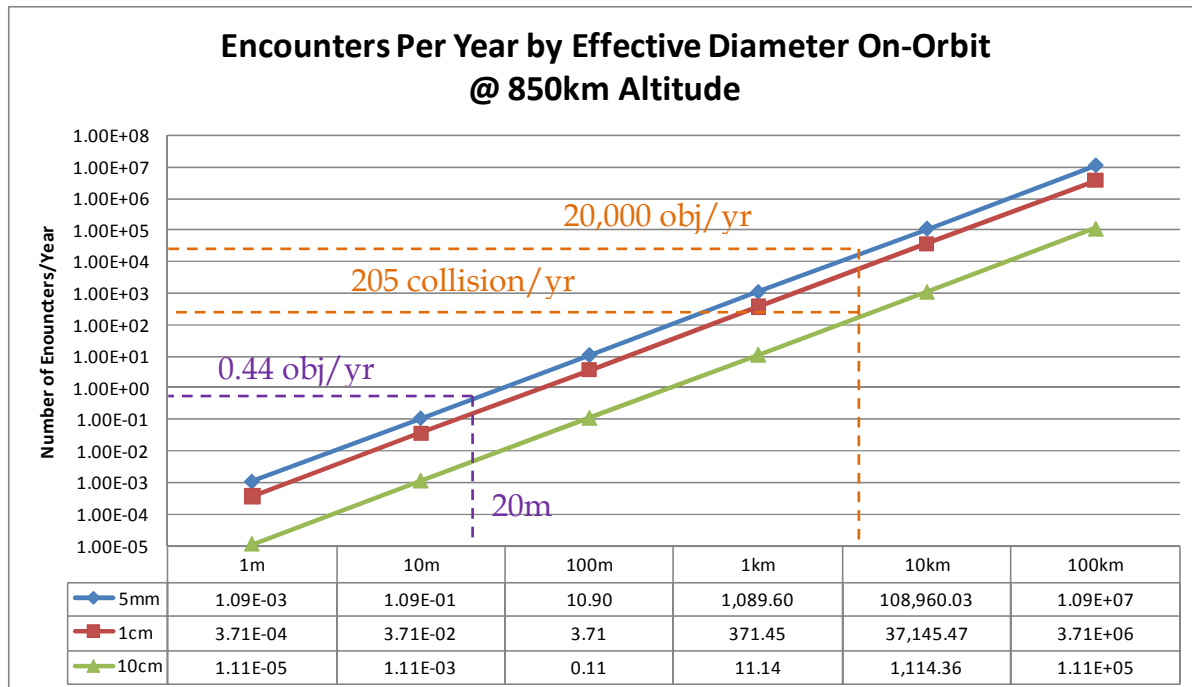


Figure 21 – A 20 m sweeper would not likely encounter any debris object larger than 5 mm (purple dashed lines) , while a sweeper larger enough to remove 20,000 5mm objects would likely collide with approximately 205 large objects, creating more debris (orange dashed lines).

In addition to the inefficiency of passive sweepers there is also an associated collision risk with large debris objects and operational spacecraft. Collisions with these large debris objects would likely fragment the object creating more debris, and possibly destroy the sweeper as well. An analysis was done comparing the debris flux for both medium and large debris objects to determine the risk involved. As shown in Figure 21, if enough passive sweepers were used to remove 20,000 medium objects per year (the upper orange dashed line intercepting the blue 5 mm line), over 200 collisions with large objects would likely occur (the vertical orange dashed line intercepting the green 10 cm line), possibly including many non-maneuverable operational satellites. From this analysis it is clear that the use of passive sweepers for stabilizing the environment is extremely inefficient and entails significant risk. Their use might be more practical for recovering from a space conflict or responding to a breakup event where the debris spatial density would be much higher.

Active Sweepers

As was demonstrated above, passive sweepers are unlikely to encounter medium debris objects with sufficient frequency to provide any debris removal effectiveness. The concept of an active sweeper expands the effective radius of the sweeper by allowing it to maneuver to intercept the debris objects. Assuming 100 spacecraft are used, each sweeper would need to remove approximately 200 medium debris objects. Once again using the debris flux at 850 km, it can be shown that an effective radius of approximately 215 m would be needed to remove 200 objects in a year.

Because current technology does not permit effective detection and tracking of medium-sized debris objects from Earth's surface, every active sweeper concept examined relies on space-based debris detection and tracking, using sensors on board the sweeper or a command vehicle. Detecting, tracking and calculating intercepts in time to execute the necessary maneuvers is a huge technical challenge for this concept. If we assume objects as small as 5 mm will be detected at a range of 1,000 km (a generous assumption), an active sweeper at 850 km altitude would have approximately 91 seconds to track the

object, characterize it as a medium-sized piece of debris, calculate an intercept trajectory, execute a maneuver and have that maneuver take effect. This is based on using an average relative velocity of 11 km/s provided by NASA's ORDEM model.

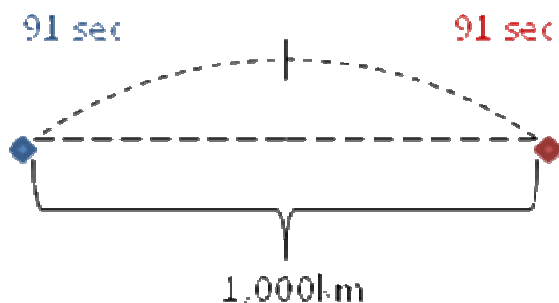


Figure 22 – The effective reaction time available for an object detected at 1,000 km is 91 sec

As was mentioned above, under this concept an individual sweeper would be required to intercept all medium debris passing within 215 m of the sweeper. Although this is the maximum distance the sweeper must maneuver to intercept any one object, the average distance would be approximately 150 m. If we ignore the time to track and characterize the object, and calculate and execute the maneuver, a velocity change of 1.7 m/s would be required to change the sweeper's orbital trajectory 150 m in any direction and intercept the debris object within the ninety seconds available. Therefore, each active sweeper would require a total annual delta-V budget of approximately 340 m/s to intercept 200 medium debris objects—a significant amount of delta-V. No previous microsat (100 kg class) with this level of high impulse delta-V has flown. Larger, existing spacecraft buses could accommodate this amount of delta-V, but the fleet launch costs would be considerable. The need to relaunch these 100 sweepers annually, or develop a network of refueling depots clearly implies a very high cost for this scheme.

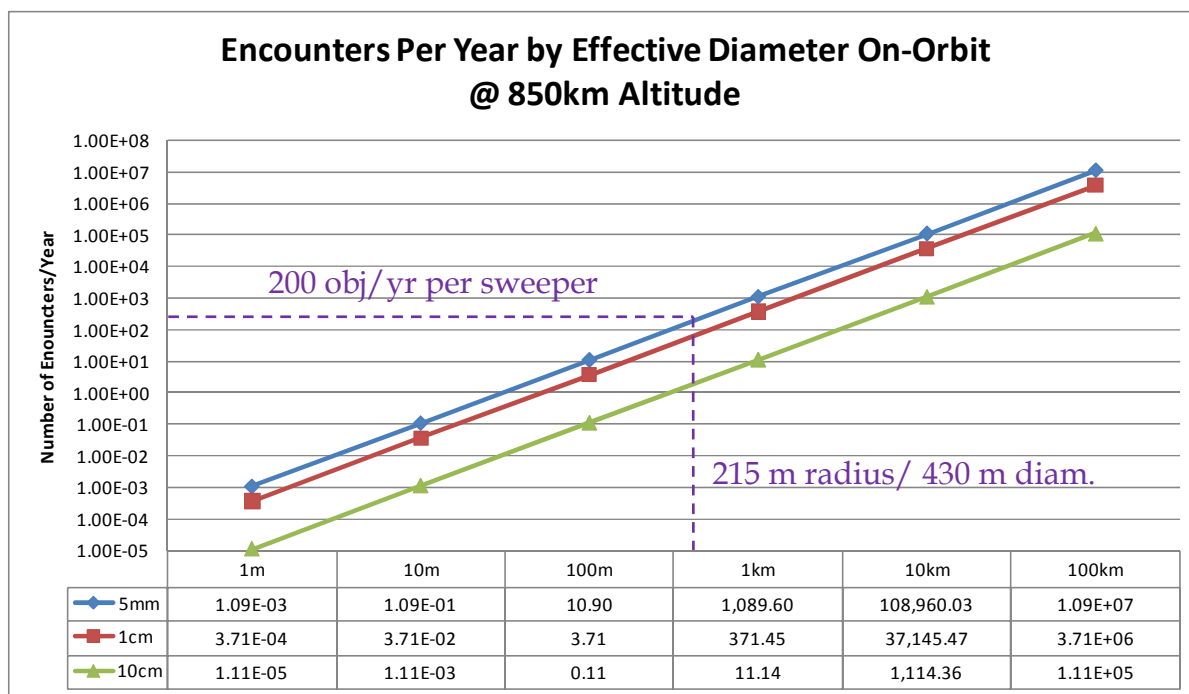


Figure 23 – Each sweeper in a constellation of 100 active sweepers must have an effective diameter of 430 m in order to remove 200 medium debris objects each year.

This analysis was also based on a constellation of one hundred active sweepers operating within a region where the debris flux is equivalent to the flux for an 850 km sun-synchronous orbit. In reality, flux levels will be much less in all other regions, necessitating even larger amounts of delta-V to intercept objects passing at distances greater than the 215 m used in this analysis.

An alternative concept for using active sweepers would involve detecting a debris object over several consecutive revolutions, and maneuvering to intercept the object on a subsequent revolution. By greatly increasing the time allowed for intercepting the debris object this concept could conceivably reduce the delta-V required per object swept. Several conjunctions of decreasing range between the sweeper and a debris object would occur for several revolutions prior to the object passing within 215 m of a sweeper. The rate at which the range decreases would vary depending on the orbital parameters of the sweeper and the debris object. However, by analyzing the rate of change between these consecutive conjunctions the sweeper might be able to calculate the maneuver necessary to intercept the debris object on a subsequent revolution. And because the maneuver has longer to take effect the delta-V required would be much less than was described for the concept outlined above in which the sweeper detects and intercepts the debris object in one revolution. However, predicting conjunctions on upcoming revolutions will be difficult, particularly for smaller objects, which generally have higher area to mass ratios and are therefore more susceptible to perturbations from atmospheric drag and solar radiation pressure. Figure 24 shows the delta-V required to remove 20,000 objects in a high density environment given the number of active sweepers used.

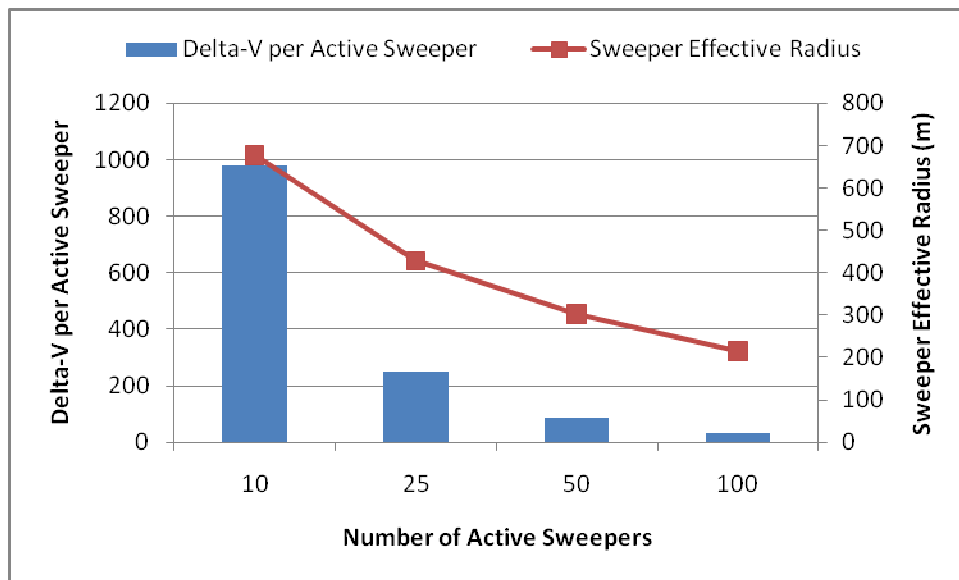


Figure 24 - The delta-V required to intercept debris objects increases exponentially as the number of sweepers decreases and required effective radius increases.

Geostationary Orbit

Because of the much lower debris spatial density and more constrained spectrum of orbit characteristics in GEO, passive and active sweepers would be inefficient systems to use for stabilizing the environment in this region. However, active sweepers might have some application in response to a breakup event, if a response can be launched quickly enough. One possible concept would involve placing active sweepers in slightly eccentric orbits with either the perigee or apogee at geosynchronous altitude. Because the sweeper has a slightly different orbital velocity than the debris it will move through the debris cloud sweeping out debris each time it reaches geosynchronous altitude. Yet, within a few

days the debris spatial density will likely drop below that of the highest density LEO orbits used in the analysis above. Therefore, placing the sweepers in orbit quickly or pre-positioning is critical to success.

Material Composition

Even if sweepers could be deployed in a way to generate enough encounters with medium debris objects to make their use practical, while avoiding collisions with large objects, they must be made from material that is effective for stopping, retarding, or shattering the medium-sized debris. The material must be lightweight to minimize launch costs, yet strong enough to withstand hypervelocity impacts with debris objects up to approximately 10 cm. Otherwise, the sweeper will generate more debris than it removes. Lightweight aerogel and foams are frequently proposed for this purpose. However, a study²⁸ conducted by JHU in support of the Catcher's Mitt study concluded that even a twelve ton sweeper with a radius of 30 m has little chance of significantly slowing debris much larger than 4 cm. Multi-layer shielding or metallic foams may have greater survivability and stopping power, but at the expense of increased mass.

Summary

From the above discussion it can be seen that the use of passive sweepers cannot reasonably be expected to stabilize the population of medium-sized debris objects. The exceptionally large number of objects that must be removed and the low flux levels that would be encountered make passive sweepers an inefficient and costly concept for debris removal. Likewise, active sweepers have been shown to be inefficient except in large numbers, and then only if an effective concept of operations is developed for their use. Sweepers might have more applicability in situations involving a higher than normal debris spatial density (e.g., recovering from a space conflict or responding to an on-orbit breakup), but only if constructed from an appropriate lightweight yet durable material.

5.2.2 Debris Removal Via Liquid/Gas/Particulate Cloud

The effective aerodynamic drag on pieces of debris (both large and small) could be increased by injecting a cloud of gas, liquid or sub-millimeter sized particulate matter into a target orbit. While these clouds would affect all objects in a given orbit (including operational satellites), small pieces of debris have much larger ballistic coefficients and would therefore disproportionately be affected by this artificial increase in atmospheric density. Therefore, this method is primarily intended for use in recovering from a space conflict where the effect on operational spacecraft is less of a concern or, more particularly, in response to a significant event such as an on-orbit breakup. Because there is no atmospheric drag to remove the cloud from the GEO belt once deployed, the application of this concept is generally limited to LEO. However, for particles smaller than 10 μm , solar radiation pressure may indeed push the material out of GEO.

Previous analysis has shown that removing even 5-10 of the most massive objects from orbit annually could markedly impact the future debris population positively. It could be very advantageous to try to find some means to remove orbital debris without putting any mass into orbit (i.e., remote option vs. *in situ*). Using a remote option could be potentially less expensive, less risky (i.e., less chance of making more orbital debris), and easier to monitor to prevent misuse. Remote options might include

²⁸Marshall H. Kaplan, Bradley Boone, Robert Brown, Thomas B. Criss, Edward W. Tunstel, Engineering Issues for All Major Modes of In Situ Space Debris Capture, AIAA-2010-8863, August 2010.

ground-based directed energy or use of ballistic trajectories. The concept of ground-based lasers is addressed in the subsequent section.

There are two primary options for using ballistic trajectories to (1) either intercept and “drag down” the objects or (2) create a temporary, high atmospheric density environment to affect orbital debris. The ability to intercept and grapple at high relative velocities (i.e., (1) above) is very difficult due to the mechanical stresses that the grapppler would have to withstand and the speed at which actuators would have to function. This would require an astonishing technology leap beyond current grappling systems and may be worth reconsidering at a later date.. However, the creation of a temporary environment is considered more carefully as the temporary environment may be created with liquid, particulates, or gas. An examination of a gaseous release within a thin balloon launched into a ballistic trajectory will be used as a nominal example to determine the potential utility for this class of debris removal.

The scenario examined assumes that if an object is moved to a 300 km circular orbit then it has been “reentered”. Three different sizes of balloons (10 km, 50 km, and 100 km) and circular orbits ranging from 500 km to 1000 km are used with three types of debris pieces by ballistic coefficient (BC) of 0.1, 1.0, and 10 m²/kg. These three BC values equate to derelict payloads, trackable debris (~10 cm diameter), and nontrackable, 5 mm, debris fragments, respectively. The density of gas modeled in the balloons is equivalent to Earth’s atmospheric density at 100 km. In essence, these balloons provide an instantaneous drag impulse equivalent to being at 100 km altitude but at orbital velocity.

A closed form analytic representation for the reduction in an orbit’s semi-major axis (a) from a high density impulse is used:

$$\Delta a = -2 \pi \delta a^2 \rho_c \quad \text{Equation 1}$$

Where: $\delta = F A C_D/m$ and $F=1$ (assume circular atmosphere)
 A, m, C_D = cross-sectional area, mass, and coefficient of drag of debris, respectively
 ρ_c = impulsive density

The impulsive equation is given for a single orbit so one must determine how many balloons are needed to create an entire orbital ring of the higher density “atmosphere”. For 10 km diameter balloons it would require about 4000 balloons, 50 km diameter → ~800 balloons, and 100 km diameter → ~400 balloons. The figure below depicts the effectiveness of these gaseous, ballistically-propelled balloons against orbital debris. It is seen that the smallest objects (largest ballistic coefficient) are the most sensitive to this removal approach – only tens to hundreds of 100 km balloons are needed to remove debris. On the other end of the utility scale is the small balloons (10 km) against the largest objects (smallest BC), requiring 10,000’s of balloons.

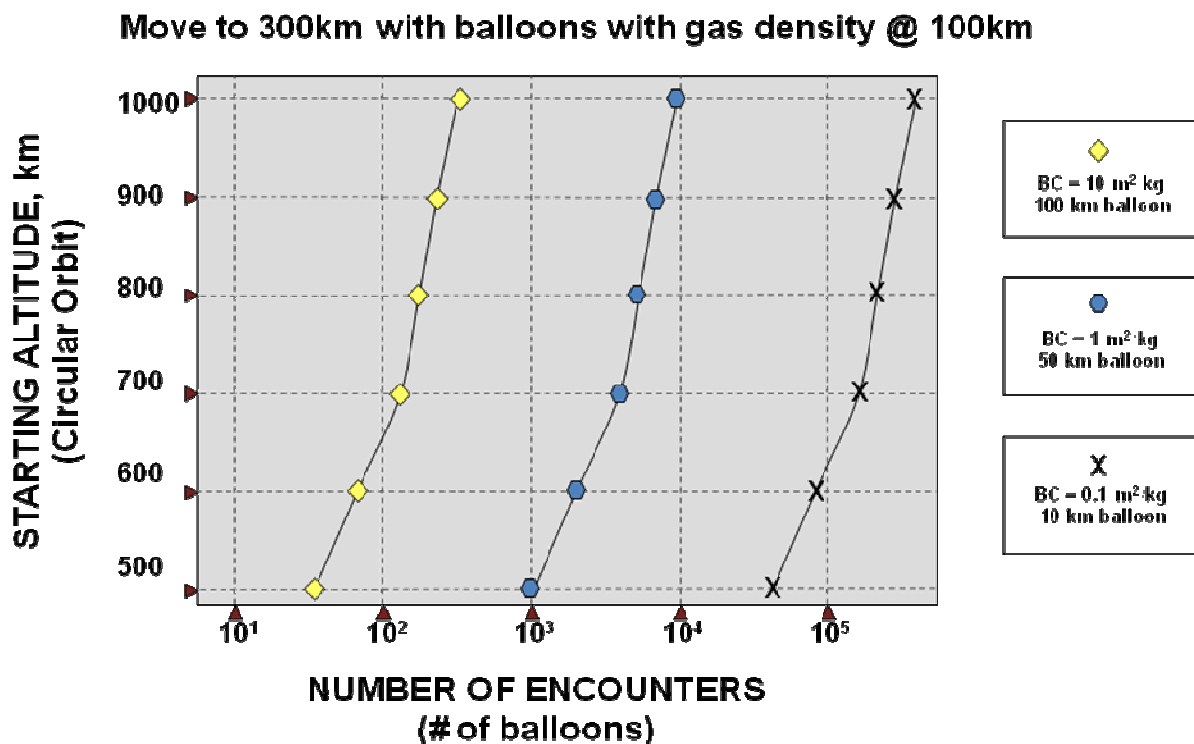


Figure 25 – The number of gaseous balloons of various sizes required to deorbit debris objects will grow exponentially as the ballistic coefficient of the targeted debris decreases.

The use of more persistent dust clouds vice gas clouds might provide some benefit in the tradeoff between volume swept, objects encountered, and impulsive force provided by the material to derelict objects. However, as the cloud contains larger and more durable particulates the effect on operational spacecraft will need to be further scrutinized.

5.2.3 Electromagnetic Forces

Another proposed method for orbital debris removal is the use of electromagnets in orbit to impart a force on debris objects either to reduce their orbital lifetime or to consolidate them for later disposal. One or more spacecraft with large electromagnets onboard would be launched to produce this effect. In Appendix A the technical fundamentals of an example of this approach are examined. From that analysis, Figure 26 shows a key finding wherein the magnetic force falls off to less than a dyne (10^{-5} N) in less than a half a kilometer for even the largest piece of ferromagnetic medium category debris (e.g. 10 cm diameter iron sphere).

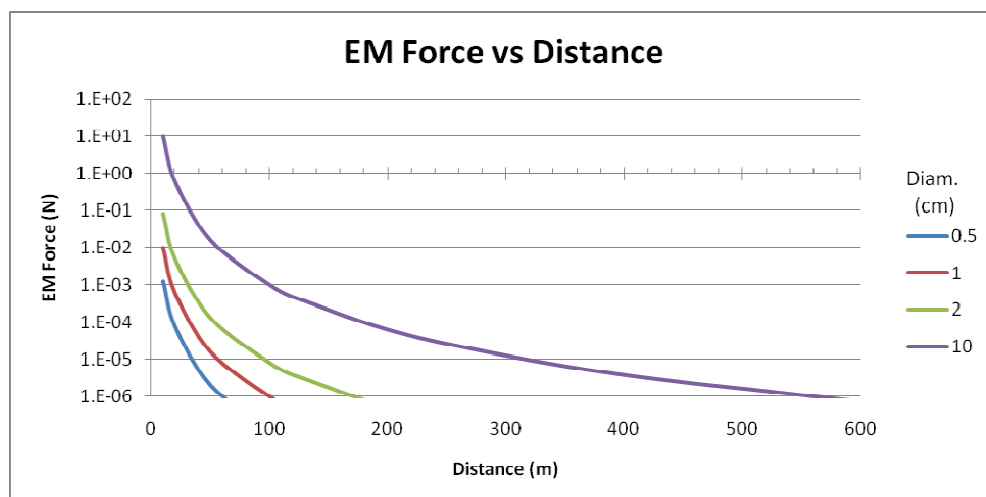


Figure 26 – Electromagnetic force versus distance showing that the magnetic force falls off to less than a dyne (10^{-5} N) in less than a half a kilometer for even the largest piece of medium category debris.

As can be seen from Figure 21, approximately 10 medium debris objects would be expected to pass within 50 m of the spacecraft each year. Assuming it were possible to actively steer the generated magnetic dipole to maintain the magnetic force constantly perpendicular to the path of these objects, a best-case ΔV of 0.000036 m/s could be exerted on these debris objects as they pass within 50 m of the electromagnet. A single pass producing this magnitude of impulse will clearly not produce the desired effect. Increasing the total ΔV by arranging multiple encounters is also problematic because these objects are untrackable. The previously discussed on-board fuel problem exists to maneuver and attempt to encounter such an object after the first pass. Even if the near-future orbit of the object could be perfectly predicted, any conceivable fuel supply would rapidly be depleted performing rapid maneuvers with a large, electromagnet equipped spacecraft.

Another fundamental question is, of course, what percentage of orbital debris is susceptible to magnetic influence. A recent study²⁹ by NASA JSC estimates that less than 10% of orbital debris by mass is high density and potentially magnetically reactive. The two bounding cases for using this information being that we can either only affect 10% of debris objects or we can weakly (10%) affect all objects. This additional information further detracts from the feasibility of the previous analysis.

In summary, the field strength of electromagnets falls off at such a rapid rate (with inverse of distance to the third power) that the radius of effect is too small to impart significant changes in orbit to even the most ideal debris targets, and therefore require an impractical number of electromagnetic systems to stabilize the debris environment.

²⁹ John N. Opiela, "A study of the material density distribution of space debris", Advances In Space Research, 2009.

5.2.4 Debris Removal Via Laser

Introduction

There are several steps to consider in evaluating the efficacy of lasers for orbital debris removal as examined in detail in **Appendix B**. The framework shown below is equally applicable to the removal of either (1) lethal, nontrackable fragments while the laser is in a stare mode or (2) large derelict objects with the laser in a track mode. Exposure geometry is the ability to illuminate the target population of orbital debris, while laser physics represents the ability to place sufficient irradiance on a debris target to cause ablation of debris surfaces. The ablation then must be of sufficient intensity and appropriate orientation in order to accelerate orbital decay. The exposure geometry and laser physics are assessed independently and then combined to determine the on-orbit debris removal efficacy for lasers for each scenario.

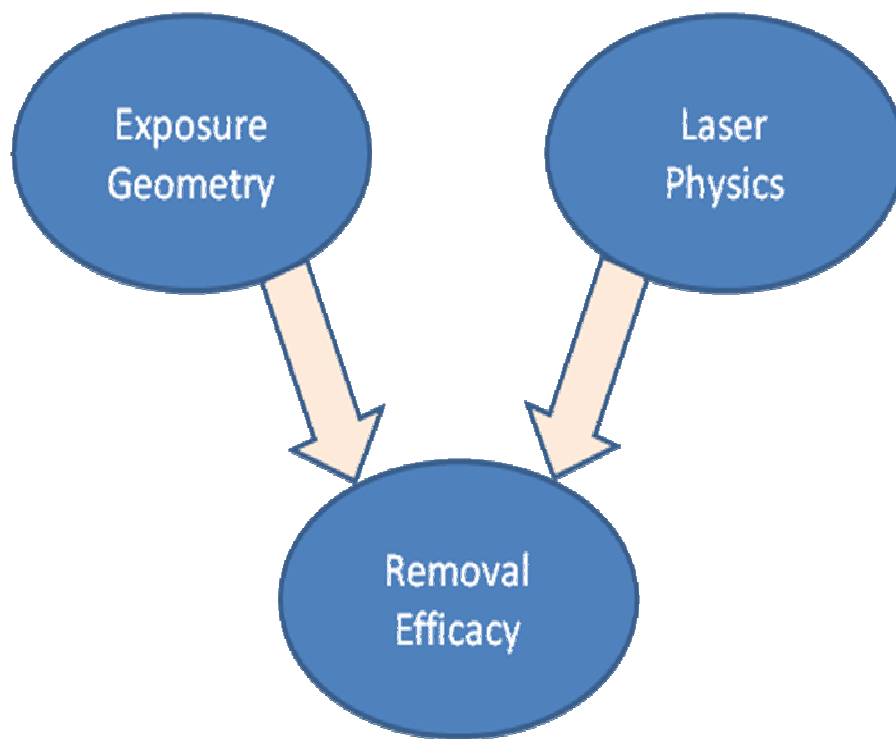


Figure 27 - The efficacy of debris removal via lasers considers both exposure geometry and laser physics.

Factors that will decrease the effectiveness of the use of laser removal in either scenario are the characteristics of the debris that is being targeted to include both surface features and dynamic tumbling. Orbital debris will have many and varied constituents from phenolics and epoxies to aluminum, steel, and tungsten. The shapes and surface characteristics will even be more varied as the fragmentation process will cause debris fragments to characteristically look most like “corn flakes” with uneven surfaces and inconsistent contours. Additionally, fragments produced from explosions and collisions have been seen to have a bit of black, carbon residue deposited on them from the detonation related to the fragmentation process. All of these observations contribute to the insight that whatever laboratory tests are conducted showing impulse coupling for bare aluminum, the actual coupling that could be realized in operations will be several orders of magnitude less.

Just as surface characteristics of orbital debris will make the impulse coupling less efficient, so will any tumbling that the derelict object might be experiencing. This will detract from the optimum effects for two reasons. First, the tumbling will cause the fragment to present a different surface to the laser over time thus making it more difficult for a plasma to be created and hence, for any impulse to be generated. Secondly, with the varied orientation relative to the laser impingement any impulse created might be imparted in a non-optimum direction, further eroding any potential reduction in the orbital lifetime of fragments from laser irradiation. The magnitude of this erosion of energy coupling has not been quantified but is likely to add at least another order of magnitude reduction in efficiency.

Removal of large objects in track mode

The primary difficulty in moving/removing is creating sufficient force on the derelict object to produce a significant change in the altitude of the object. While a sophisticated tracking system might be able to keep a single laser beam on a single object for a portion of the derelict object's track over the laser site the increased time on target is counteracted by the larger impulse required.

A laser must be capable of providing high energy pulses sufficient to create a recoil effect on the debris through the creation of a plasma. The only candidate large enough for this application is located at the National Ignition Facility (NIF) where this high peak power (~TW with a 4ns pulse) and large energy laser is capable of being fired only once a day. It is unclear whether such a device could be operated in a multi-pulse mode in the near future. However, calculations of realistic energy coupling for the small end of the large object spectrum (i.e. 10cm and 1kg) requires hundreds of pulses to provide a 10km change in altitude under optimum geometric orientation of the site to derelict object orbit.

More practical systems are in the 100-kW range and most of these are in the planning stages for repetition rates on the order of pulses per day where final viable designs will likely have to be able to operate at many tens of kW's and several pulses per second. In summary, the pulse frequency would have to be increased several orders of magnitude to even permit one site to impart sufficient energy to a single 10 cm object each day to move tens of kilometers.

For trackable objects (above about 10 cm in diameter) element sets are available to provide tracks to within 1 km. Laser site specific capabilities would then have to be used to provide a more precise track if a small spot size can be applied to orbiting objects. However, the requirement to insure that the impulse provided serves to reduce the object's orbital lifetime vice increasing it, may limit the encounter time by limiting the opportunities for illuminating the objects.

Analysis by AFRL suggests that a Laser Guide Star (LGS) must not only be used but must lead the small, dim debris fragment. Even this will not correct for the tilt anisoplanatism effect in the atmosphere. So while optimum atmospheric compensation will contribute to irradiance on target it will not be sufficient to get the irradiation even to within several orders of magnitude of what is needed. The beam divergence of the laser energy will cause yet another large, several orders of magnitude, reduction in energy to the target. No matter which size of debris is being pursued a breakthrough is needed in atmospheric compensation capabilities to correct for the probable several orders of magnitude increase in spot size from a state of the art laser for propagation of around 1000 km.

Using laser systems that might be available within decades, likely performance of large object removal by lasers would require tens to hundreds of ground sites to remove a single object over a year.

Removal of medium debris in stare mode

The primary difficulties identified with using a laser to deorbit medium, nontrackable debris are the ability to compensate for beam scattering due to the atmosphere, appropriate geometry between the laser and the orbiting debris object, number of objects likely exposed by a laser in a stare mode, and the magnitude of the impulse that could reasonably be delivered.



Figure 28: Ground based laser³⁰

Figure 29 below shows the engagement geometry results for operating a laser in stare mode – there can be many encounters with debris each year, but only if the laser spot is made very large (lines on the figure show results for 20 m spots and 1 km spots). From Figure 29, it can be seen that illumination areas of 100 m would only expose the laser energy to 10 objects per year for 5 mm objects. Since the performance threshold is on the order of ~20,000 lethal fragments removed per year this would result in hundreds, if not thousands, of ground laser sites to execute even with the liberal assumptions prescribed thus far.

To correct for this reality, the required more powerful beams would require prohibitively large laser systems on the ground and must be oriented to provide the most effective debris illumination that occurs at limited elevation ranges which again creates great attenuation of the laser energy. This is true since pointing straight up provides the laser propagation that minimizes atmospheric effects but shooting straight up will not produce the hoped for orbital decay to most debris encountered. The width or area of the affected region can vary drastically depending on the design of the laser and ability to keep the laser collimated for long distances. A 40 cm lower end size is one that matches with the laboratory tests for irradiance on surfaces and related energy coupling while 100 m is the dimension required to provide wide enough coverage to statistically assure that some number of medium debris fragments might be exposed if the laser were used in a stare mode. If the beam spot is on the order of centimeters immediately out of the laser, then the irradiance will drop rapidly with range. For that reason, the transmitter diameter must be large on the ground. In fact, it must be much larger than the 1 cm laser size if the beam diameter is to be made small at the debris. For example, the transmitter diameter must be at least 1 m to produce a 40 cm spot at 150 km.

By the time the beam traverses 400 km, it will have grown to about 1 m in diameter. Both of these distances are not even far enough to be useful for debris removal applications since objects that close will reenter due to atmospheric drag on their own. The resulting drop in energy is due to beam divergence (diffraction), where even a collimated beam will have its beam diameter grow linearly with

³⁰ Beletsky, Yuri, European Southern Observatory, <http://www.eso.org/public/images/potw1036a/>, August 2010.

distance. Means to insure that an effective spot size of a high power laser could be kept near 1 m would provide a useful capability that could provide a solid foundation for energy delivery to orbit though it would require significant active compensation of the beam propagation for around 100 km range, well short of any useful debris removal applications.

Generating a laser spot that is large and still providing sufficient energy on target requires an extremely large and, currently impractical, laser device, as well as substantial beam control performance.

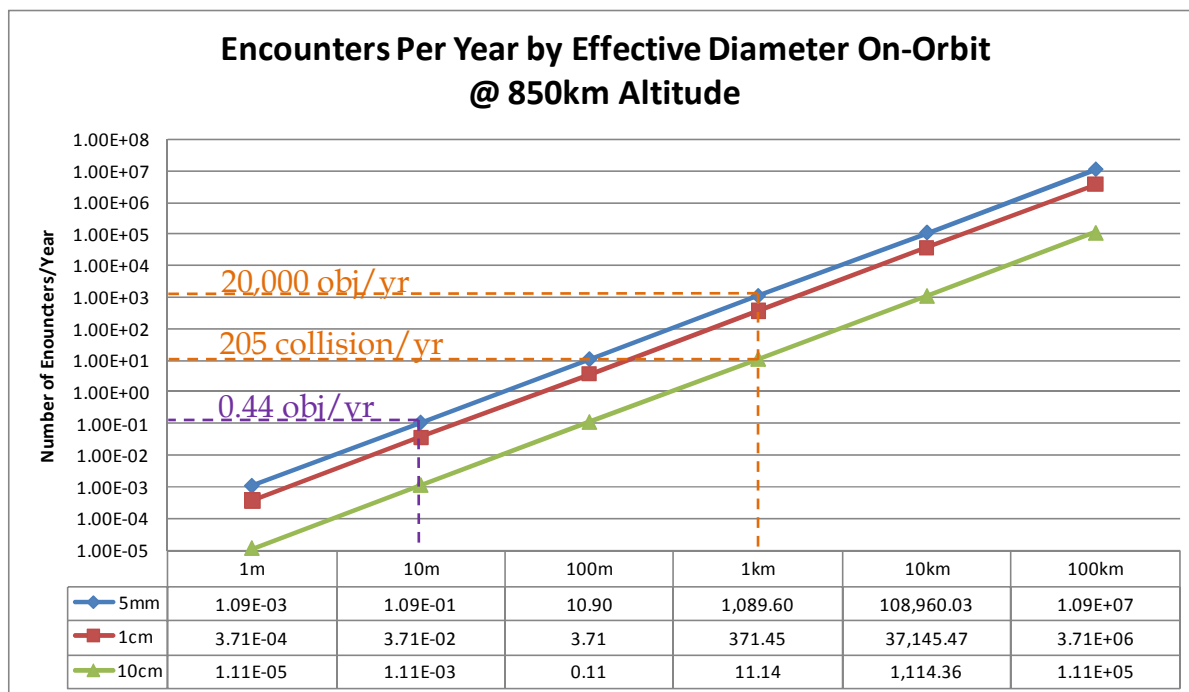


Figure 29 - Despite the collision hazard from small debris, very large spot sizes are required for ground-based laser systems to encounter a significant number of debris objects in a stare mode.

For an object in LEO being observed by a fixed ground location in stare mode, encounter time will range from 6 microseconds to 14 seconds. These illumination times are based on a laser staring in one fixed elevation and azimuth with a width of illumination between 40 cm and 100 m. The low Earth orbiting objects travelling at approximately 7.6 km/s will yield the range in exposure times.

It is infeasible to increase the time on target by tracking the debris in concert with illuminating them. Objects in the 5mm – 10cm size range are too small to be precision-tracked by ground radars and optical sites since they cannot be reliably detected and correlated.

To move a 5 gm object from 1,000 km to 300 km, where it will reenter on its own, requires a delta-v of around 150 m/s imparted in the anti-velocity vector direction. As a result, the impulse that must be imparted to the object is 5 gm x 150 m/s or 0.75 kg·m/s. Assuming a fluence of 28.3 J/cm² (from AFRL test results) and an impulse coupling coefficient of 2.5 dynes·s/J for a 1.06 μm wavelength laser with a pulse width of 30 ns yields a requirement for around 1,000 pulses (if the debris area is 1 cm²). With a restricted elevation range, the current technology that permits such high powered pulses to be executed one at a time, indicates the low confidence in the debris removal executing the change in orbit required. This physical effect was calculated using the 40 cm exposure area which would operationally result in statistically “never” seeing a medium piece of debris when operating in a stare mode.

In order to perturb an object's orbit to cause a decrease in its orbital lifetime with high confidence the laser energy must be imparted against an object's orbital velocity. As a result, engagement of debris will have to occur at elevations well below 90° on the approaching portion of the orbit. Since there is a radial component to the resulting interaction, it is desirable to engage lower in the sky if possible. This constraint will significantly increase the "slant" range, thereby dramatically reducing energy on target. It also forces the laser beam to traverse the worst part of the atmospheric turbulence, which will inevitably broaden the beam in space. The constraint will also decrease opportunities to see and affect objects as the majority of the possible engagement times will not be effective for reducing the object's lifetime. Assuming effective laser interactions, to reach the performance threshold of ~20,000 medium objects removed per year one must have hundreds to thousands of ground sites or improve the overall laser system performance by several orders of magnitude.

Space-based versus ground-based modes of operation

Ground-based lasers would be limited to use on objects in LEO orbits. While space-based lasers reduce the issues of range, atmospheric, and object detection to some extent relative to ground-based lasers, cost and complexity (both technical and political) increase drastically.



Figure 30: Space based laser³¹

Moving a laser to a space-based platform reduces the need for atmospheric compensation and potentially decreases the range to potential debris. However, the laser necessary to provide any sufficient irradiance for space-to-space ranges is not yet in existence. Hypothetical systems proposed would not provide sufficient irradiance and resulting impulse to make debris removal viable. The significant and uncertain coupling of laser energy to coarse tumbling debris will still need to be addressed for space-based applications.

Summary

The use of a ground-based laser to move/remove even medium-sized (5mm to 10cm) debris, much less intact derelict objects, is not likely to be effective with current technology. The number of objects exposed to a laser, given the geometric constraints, coupled with the poor predicted irradiance on these limited fragments makes it mathematically unrealistic that a substantial number of objects could be moved/removed. More specifically, even using the most optimistic energy propagation energy coupling assumptions it would require the operations of many hundreds of ground-based laser sites to insure the stabilization of the lethal debris probability of collision (i.e. remove ~20,000 medium-sized fragments from LEO annually). However, if several of these issues can be simultaneously corrected while the state

³¹ Federation of American Scientists, Space Based Lasers, <http://www.fas.org/spp/starwars/program/sbl.htm>, August 2010.

of the art in lasers is also enhanced significantly, the viability of laser removal of debris may be enhanced. Yet, the coupling of laser energy to coarse, dirty, tumbling debris is an issue that requires significant analysis to even quantify its impact, much less be able to solve the problem. In short, any proposed laser concept, whether ground-based or space-based laser, must be scrutinized very closely, and our assessment is that they are unlikely to be effective for debris removal in the near future. At a minimum, a demonstration program would have to prove the viability of any concept.

For either mode of laser debris removal, the current operational constraints of the Laser Clearing House (LCH) must be significantly modified. As stated by AFRL's analysis, any laser that points above the horizon will require "shot-by-shot approval" from the LCH. With the number of pulses required to affect debris orbits the current process of the LCH would have to be substantially modified for laser removal to be allowed to operate even if the process appeared to be effective.

One technology that is currently immature is ground-based laser-plus-Space Relay Mirror (SRM), and that could present a long-term solution, since the atmosphere can in principle be well-corrected and the laser device can be on the ground. However, the debris tracking from such a platform would still have to be quite excellent and the system issues would still need to be scrutinized and demonstrated. For both space-based and ground-based laser systems, the political and legal hurdles for their deployment will definitely be substantial.

6 Conclusions

Policy must be addressed

There is concern that an active debris removal system could be used as an ASAT capability. Although, for advanced space programs, development of an operational ASAT capability is technically simpler than debris removal, and therefore, there is no technical justification for this concern. Additionally, significant treaty constraints exist that block the removal of debris caused by other nation's launches. A potential path to deal with these concerns would be to make the effort international from the beginning.

Development of a debris removal capability should begin soon

Orbital debris in LEO is a growing problem that already imposes probable costs on asset operators and will not be solved by the current, voluntary mitigation guidelines. Nor can the problem be solved with improved shielding or collision avoidance maneuvers. Current design practices generally allow spacecraft to survive impacts with debris of 5 mm or less. Providing collision avoidance information to maneuverable spacecraft allows them to avoid larger debris, 10 cm and up. Armoring spacecraft to survive collisions with 5 mm to 10 cm sized debris is not economically feasible and is likely not technically feasible. Providing collision avoidance information to active spacecraft for the hundreds of thousands of these medium sized debris objects will only be of potential benefit to the subset of maneuverable spacecraft which can actually act upon that information. Even then, the information provided would have to be radically improved beyond current capabilities to avoid unnecessary avoidance maneuvers, which would rapidly deplete spacecraft lifetime fuel reserves. Therefore, active debris removal will be required at some point to maintain acceptable operational risk. Although projections show that it may take decades for the risk in LEO to become unbearable, it may take a similar timeframe to develop the necessary technical solutions and to negotiate an acceptable agreement given the significant legal and policy considerations. Moreover, there is a finite probability that a new collision or ASAT test in the near term will accelerate the projected debris growth, requiring a remediation solution significantly faster than currently projected. In GEO, on-station failures of assets prior to their removal from the GEO belt will at some point in the future cause operational constraints within popular longitude bands and require the removal of derelict systems.

The 2010 Deepwater Horizon oil spill exemplifies the need for readily available mitigation and remediation methods. In the case of the Deepwater Horizon oil spill, a remedy was available to stop an oil leak at relatively shallow ocean depths. It was assumed that these techniques could be effective at greater ocean depths, but were never tested. Once the oil spill began it was quickly realized that the techniques used for shallow depth oil spills were not effective, leaving officials scrambling for a solution. Not only do officials need a means to remedy the situation, they also need to know that the particular technique works and that it can evolve to meet future challenges. A similar situation could occur with orbital debris. If a significant event happens in orbit and decision-makers are not properly prepared to remedy the situation, it could grow into a catastrophic event. The longer the community waits to address the problem, the higher the remediation costs will be.

Development should concentrate on pre-emptive removal of large debris in both LEO and GEO

Table 2 lists each of the scenarios discussed in Section 4, and identifies which debris size is applicable for that scenario in each orbital region. Any discussion of an orbital debris removal program or system should be limited to those cells colored green.

		Stabilize the Environment		Recover From a Space Conflict		Respond to a Significant Event	
		Applicable?	Solution?	Applicable?	Solution?	Applicable?	Solution?
LEO	Medium Debris	Yes	No	Yes	Maybe	Yes	No
	Large Debris	Yes	Yes	No		No	
GEO	Medium Debris	No		Yes	Maybe	Yes	No
	Large Debris	Yes	Yes	No		Yes	Yes

Table 2 – Shows which debris removal scenarios are applicable for each debris size in both LEO and GEO.

No reasonable solution was found to effectively combat medium size debris (approximately 5 mm to 10 cm) in LEO, except possibly for recovering from an extensive space conflict. For all medium debris stabilization solutions examined, even if the technical barriers to the proposed solution were overcome, an unreasonable number of systems would be required to stabilize the environment, often measured in the thousands. Moreover, the timelines for debris dispersal after a significant event do not support an effective response. As such, effective mitigation coupled with the pre-emptive removal of the sources of future medium debris, is by far the most cost-effective solution to the LEO debris threat. NASA has suggested that removing 5 to 10 of the largest objects in LEO with the greatest risk of collision could stabilize the current medium sized debris population when combined with improved post-mission spacecraft disposal rates. A cost-effective solution, or set of solutions, that can achieve this without imposing operational constraints on existing assets should be the goal of an effective development program to tackling the LEO debris problem. Any potential solution must be able to rendezvous with and exert control over a variety of large debris objects, including those possessing significant amounts of residual angular momentum. A viable machine vision technology will likely be required as well, and objects encountered are unlikely have convenient attachment points, so any grappling solution must address that challenge.

Although it is clear that the debris spatial density (and collision risk) in GEO is lower than in LEO, the threat from failed spacecraft in that singular orbit can impose significant operational difficulties to assets the GEO belt, as illustrated by the recent Galaxy 15 failure. Additionally, the propellant necessary to transfer a GEO asset to the graveyard orbit (GEO + 300 km) at end of its operational life has significant value toward extending that lifetime instead. As such, solutions that can effectively relocate failed or fuel-depleted spacecraft from the GEO belt to the graveyard orbit would be of significant value, and likely can close a business case in the near term, as well as providing the capability to help stabilize the GEO debris environment or to respond to an unexpected spacecraft failure. Conversely, technical solutions to large object removal in GEO can serve as stepping stones to a capability to refuel or even repair high value GEO assets.

The study also examined potential solutions for recovering after a space conflict in both LEO and GEO. This scenario was specifically examined due to the military need for a rapid debris removal solution in this situation and the associated technical difficulty. All examined solutions to this scenario imposed risks to operational assets or were not reasonable considering the current debris spatial density, however, neither of these concerns is likely an issue after a space conflict and therefore acceptable solutions may exist. Given the low probability, high consequence nature of this scenario, it may be difficult to sustain a development program to address this particular problem.

Appendix A: Debris Removal Via Electromagnetic Forces

Another proposed method for orbital debris removal is the use of electromagnets in orbit to impart a force on debris objects either to reduce their orbital lifetime or to consolidate them for later disposal. One or more spacecraft with large electromagnets onboard would be launched to produce this effect. In this section we will examine the technical fundamentals of this approach ignoring complicating affects of the earth's magnetic field and spacecraft charging.

Force Imparted by an Electromagnet

For a piece of debris (D) and an electromagnetic (M), the far-field magnetic force (F_{DM}) is shown in Equation 2³².

$$F_{DM} = (3/2\pi) \mu_0 (\mu_D \mu_M d^{-4})$$

Equation 2

Where μ_0 is the magnetic permeability of free space ($4\pi \times 10^{-7} \text{ N/A}^2$), μ_D is the magnetic moment of the debris object (in $\text{m}^2 \cdot \text{A}$), μ_M is the magnetic moment of the electromagnet (in $\text{m}^2 \cdot \text{A}$), and d is the separation between the center of mass of the debris object and the electromagnet. Clearly from the equation, the amount of force exerted is highly dependent on the distance between the magnet and the debris object. For a ferromagnetic debris object (e.g., iron), the magnetic moment³³ can be found using:

$$\mu_D = (\mu_A) (M)^{-1} (\rho_D) (4/3 \pi r_D^3) (N_A)$$

Equation 3

Where μ_A is the magnetic momentum per atom of the object, M is molar mass, ρ_D is the density of the material, r_D is the radius of the debris object, and N_A is the Avogadro Constant ($6.02214179 \times 10^{23} \text{ mol}^{-1}$). For iron the magnetic momentum per atom at 0K is $2.23 \times 10^{-23} \text{ m}^2 \cdot \text{A}$, the molar mass is 55.845 g/mol, and density is 7.874 g/cm³. Therefore, the μ_D for iron is:

$$\mu_D = 7.93 r_D^3 \text{ m}^2 \cdot \text{A} \quad (r_D \text{ in cm})$$

Equation 4

The magnetic momentum of the electromagnet can be found using Equation 5.

$$\mu_M = ni\pi r_C^2$$

Equation 5

Where n is the number of loops in the coil of the magnet, i is the current flowing in the conductor, and r_C is the radius of the coil. It can also be shown that for a high temperature superconducting (HTS) coil the mass of the coil (m_C) equals:

$$m_C = 2ni\pi r_C \rho_C / I_C$$

Equation 6

³² Daniel W. Kwon and David W. Miller, "Electromagnetic Formation Flight of Satellite Arrays", February 2005, SSL # 2-05.

³³ J. B. Calvert, "Iron", <http://mysite.du.edu/~jcalvert/phys/iron.htm>, December 2003.

Where ρ_C is the volumetric mass density of the coil wire and I_C is the critical current density. Combining Equation 5 and Equation 6 it can be seen that

$$\mu_M = 0.5(I_C/\rho_C) m_C r_C$$

Equation 7

Using state of the art materials and technology, the value for I_C/ρ_C is 16,250 A·m/kg. Empirical work on Electromagnetic Formation Flight satellites has demonstrated m_C would equal approximately 10% of the spacecraft total mass ($m_C = (0.1) m_{sc}$). However, a more generous 30% figure will be used for this analysis. Current heavy lift launch vehicles such as the Atlas V will accommodate payloads up to approximately 14,000 kg, and by creatively storing the magnetic coils within the fairing of one of these vehicles it is conceivable that an electromagnet with a radius of 5 m could be launched. Therefore, the maximum magnetic momentum we could expect to obtain from a space based electromagnet would be

$$\mu_M = 0.5(16,250 \text{ A·m/kg}) (0.3) (14,000 \text{ kg}) (5 \text{ m})$$

or

$$\mu_M = 1.71 \cdot 10^8 \text{ m}^2 \cdot \text{A}$$

Equation 8

Substituting Equation 4 and Equation 8 into Equation 2, the magnetic force generated between a piece of iron debris of radius r_D (in cm) and a spacecraft with a HTS electromagnet across a distance d (in m) can be calculated.

$$F_{DM} = 812 r_D^3 d^{-4} \text{ N}$$

Equation 9

Figure 31 plots a variety of values for the radius r_D and distance d .

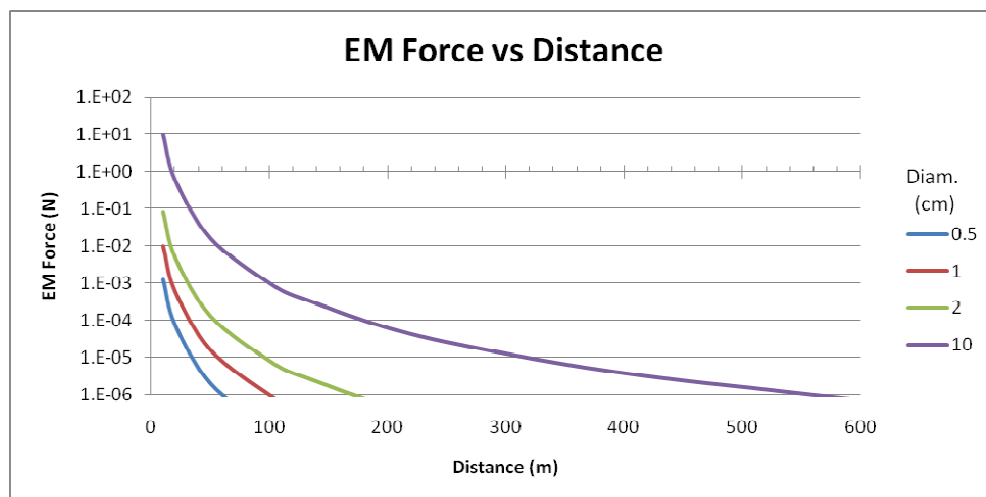


Figure 31 – Electromagnetic force versus distance showing that the magnetic force falls off to less than a dyne (10^{-5} N) in less than a half a kilometer for even the largest piece of medium category debris.

Practical Implications

As can be seen from Figure 21, approximately 10 medium debris objects would be expected to pass within 50 m of the spacecraft each year. Assuming it were possible to maintain the magnetic force constantly perpendicular to the path of these objects, Figure 32 shows the force over time exerted on these debris objects as they pass within 50 m of the electromagnet.

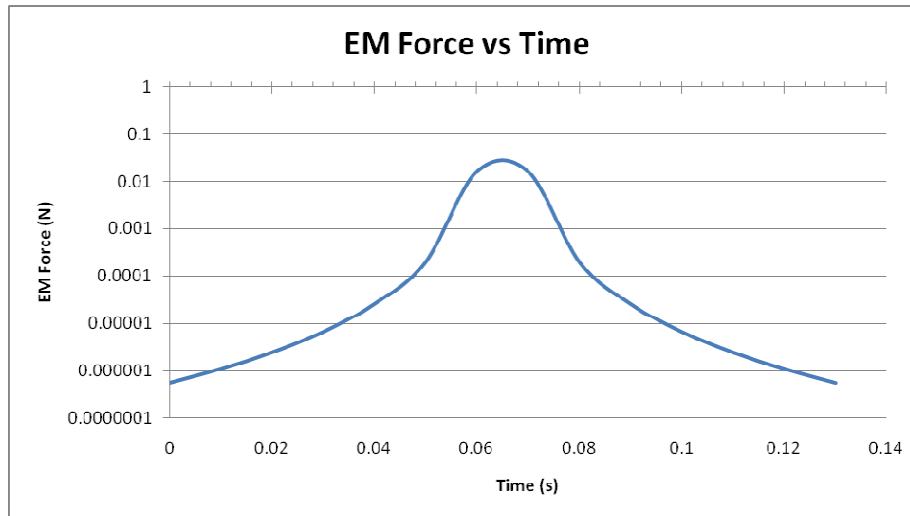


Figure 32 – The electromagnet's force on a ferromagnetic piece of debris varies greatly as the debris object moves relative to the electromagnet.

An effective impulse of approximately 0.15 mN·s can be estimated from this figure. Using a form of Tsiolkovsky's rocket equation ($\Delta v = F\Delta t / m$) in Equation 10, we find this hypervelocity near-collision imparts a miniscule delta-V.

$$\Delta v = (0.010 \text{ N} \cdot 0.015 \text{ s}) / 4.1 \text{ kg} = 0.000036 \text{ m/s}$$

Equation 10

A single pass producing this magnitude of impulse will clearly not produce the desired effect. Increasing the total delta-V by arranging multiple encounters is also problematic because these objects are untrackable. There would be no ability to maneuver and encounter such an object after the first pass. Even if the near-future orbit of the object could be predicted, any conceivable fuel supply would rapidly be depleted performing rapid maneuvers with a 14,000 kg spacecraft.

Another fundamental question is, of course, what percentage of orbital debris is susceptible to magnetic influence? A recent study³⁴ by NASA JSC estimates that less than 10% of orbital debris by mass is magnetically reactive. The two bounding cases for using this information being that we can either only affect 10% of debris objects or we can weakly (10%) affect all objects. This additional information further detracts from the feasibility of the previous analysis.

In summary, the field strength of electromagnets falls off at such a rapid rate (with inverse of distance to the fourth power) that the radius of effect is too small to impart significant changes in orbit to even the most ideal debris targets, and therefore require an impractical number of electromagnetic systems to stabilize the debris environment.

³⁴ John N. Opiela, "A study of the material density distribution of space debris", Advances In Space Research, 2009.

Appendix B: Debris Removal Via Laser

It has been speculated that ground-based lasers could be used to lower the orbits of debris. For large pieces of tracked debris, this system could target specific objects, whereas small pieces of debris, which cannot be tracked, would require a wide-beam, stare configuration. The primary difficulties identified with this concept are the ability to track small pieces of debris, beam scattering due to the atmosphere, appropriate geometry between the laser and the orbiting debris object, and the magnitude of the impulse that could reasonably be delivered. Various RFI respondents suggested ground-based lasers could be used for each of the three response scenarios. However, most envision its use for a reactive response. The fact that the laser would be ground-based limits its potential use to LEO orbits.

The use of space-based lasers was also examined. While space-based lasers reduce the issues of range, atmospherics, and object detection to some extent relative to ground-based lasers, cost and complexity (both technical and political) increase drastically.

There are several steps to consider in evaluating the efficacy of lasers for orbital debris removal as shown in the figure below which is general enough to cover both ground-based and space-based applications to remove both lethal, nontrackable fragments and large derelict objects. The exposure geometry and laser physics are assessed independently and then combined to determine the on-orbit debris removal efficacy for lasers.

Exposure geometry is the ability to illuminate a significant fraction of orbital debris on a routine basis, while laser physics represents the ability to place sufficient irradiance on a debris target to cause ablation of debris surfaces. The ablation then must be of sufficient intensity and appropriate orientation in order to slow or vaporize the debris.

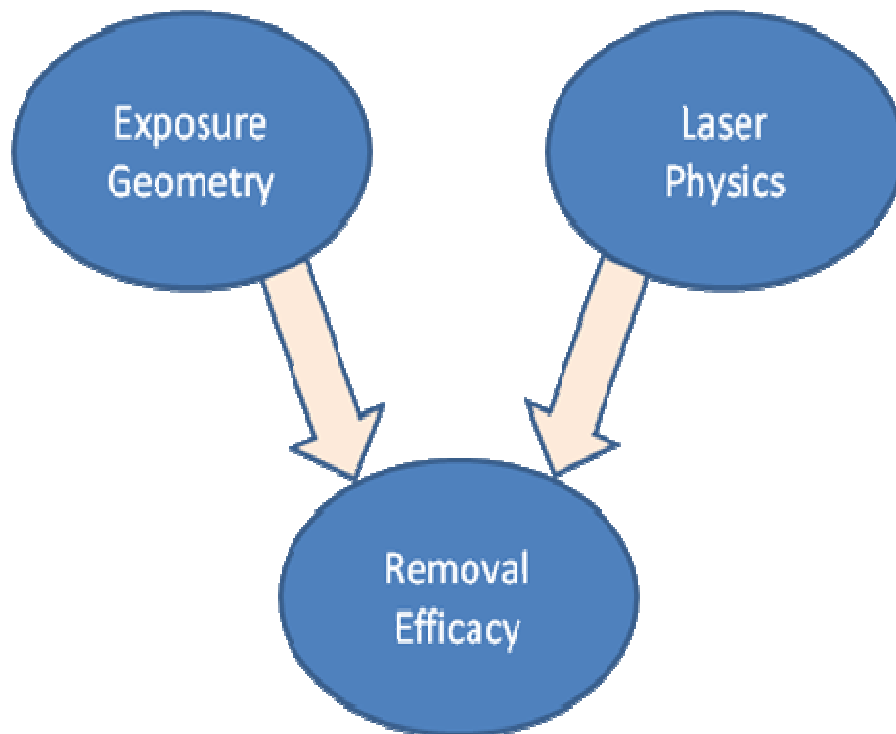


Figure 33 - The efficacy of debris removal via lasers considers both exposure geometry and laser physics.

In order to evaluate the laser concepts, we considered two options. In one case, we computed the number of debris encounters at any given altitude by assuming a very large laser spot whose irradiance is enough to cause ablation. Figure 34 below shows the engagement geometry results – there can be many encounters with debris each year, but only if the laser spot is made very large (lines on the figure show results for 20 m spots and 1 km spots). As indicated above, generating a laser spot that is large requires an extremely large and probably impractical laser device, as well as substantial beam control performance. Moreover, there are major concerns with “positive control” of the laser device, so it doesn’t interfere with space assets other than debris.

In the second case, we considered tracking a piece of debris as it transits the sky above the laser, which will provide much more time on target but adds its own issues. Throughout the course of this examination of the efficacy of debris removal using laser energy, the tradeoff and issues related to these two modes, stare mode vs. track mode, will be addressed. By default, stare mode applies to nontrackable debris while track mode pertains to trackable debris (i.e. greater than 10cm diameter in LEO).

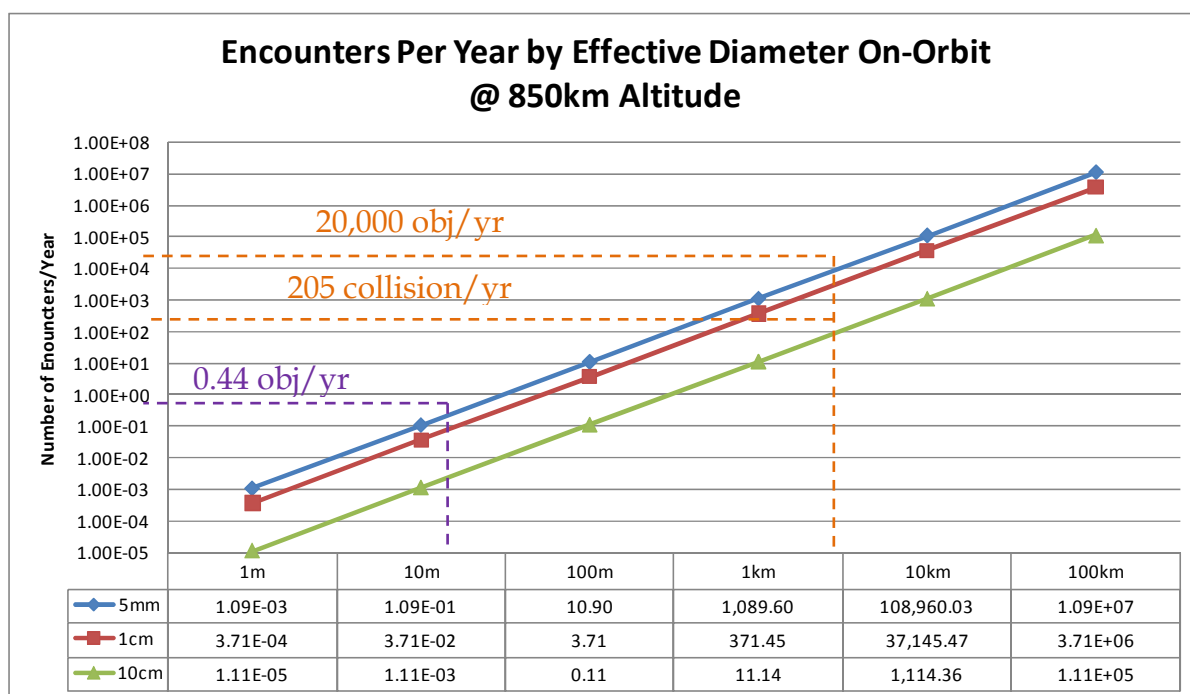


Figure 34 - Despite the collision hazard from small debris, very large spot sizes are required for ground-based laser systems to encounter a significant number of debris objects in a stare mode.

Exposure Geometry

The exposure geometry analysis quantifies the number and type of objects that might be exposed to laser devices. There are several key technical challenges that will be addressed:

- **Trajectory of debris:** Most debris is in near-circular orbits with eccentricities being lower for lower altitudes. The inclination of the debris objects range from 27 to 115 degrees with the vast majority in LEO occurring between 65-105 degrees. As a result, the trajectory of debris relative to a ground site may vary drastically by azimuth and elevation depending upon the site’s latitude.

- **Effective range:** The range over which a laser may be effective is a function of its power, wavelength, and ability to deal with atmospheric turbulence. However, the range of altitudes over which a ground-based laser will likely have to be effective is 700 – 1600 km. The range at which a laser can provide sufficient energy to cause ablation on the surface of an orbiting object is going to be highly related to both the power of the laser and the ability to perform atmospheric compensation. These issues will be covered later in the section on laser physics.
- **Effective area of illumination:** The width or area of the affected region can vary drastically depending on the design of the laser and ability to keep the laser collimated for long distances. A 40 cm lower end size is one that matches with the laboratory tests for irradiance on surfaces and related energy coupling while 100 m is the dimension required to provide wide enough coverage to statistically assure that some number of medium debris fragments might be exposed if the laser were used in a stare mode. If the beam spot is on the order of centimeters immediately out of the laser, then the irradiance will drop rapidly with range. For that reason, the transmitter diameter must be large on the ground. In fact, it must be much larger than the 1 cm laser size if the beam diameter is to be made small at the debris. For example, the transmitter diameter must be at least 1-m to produce a 40 cm spot at 150 km. By the time the beam traverses 400-km, it will have grown to about 1 m in diameter. Both of these distances are not even far enough to be useful for debris removal applications since objects that close will reenter due to atmospheric drag on their own. The resulting drop in energy is due to beam divergence (diffraction), where even a collimated beam will have its beam diameter grow linearly with distance. Means to insure that an effective spot size of a high power laser could be kept near 1m would provide a useful capability that could provide a solid foundation for energy delivery to orbit though it would require significant active compensation of the beam propagation for around 100 km range.
- **Number of Objects Exposed:** The figure used to show exposure of debris to passive sweepers is applicable to laser exposure. From Figure 34, it can be seen that illumination areas of 100-m would only expose the laser energy to 10 objects per year for 5-mm objects. Since our performance threshold is on the order of ~20,000 lethal fragments removed per year this would result in hundreds, if not thousands, of ground laser sites to execute even with the liberal assumptions prescribed thus far.

Such large beams would lead to prohibitively large laser systems on the ground. These numbers have been determined for the most populated region of Earth orbit (around 850 km), and it assumes that these objects can be illuminated at any point in this orbit. As will be seen later, this assumption is extremely optimistic since the most effective debris illumination occurs at limited elevation ranges. Instead, it might be preferable to track a single object on each pass. In that case, the focus will be on the encounter time.

- **Encounter Time:** For an object in LEO being observed by a fixed ground location in stare mode, encounter time will range from 6 microseconds to 14 seconds. These illumination times are based on a laser staring in one fixed elevation and azimuth with a width of illumination between 40cm and 100m. The low Earth orbiting objects travelling at approximately 7.6 km/s will yield the range in exposure times. Later, it will be shown that there are some practical limitations to the longer exposure time in stare mode since the energy will be so dissipated as to have no real effect while the smaller width of view provides an infinitesimally small chance of even encountering a debris object in a stare mode. From Figure 34, it was shown that a 20 m beam width would result in a 50/50 chance of encountering a 5mm particle over a year's time. It is important to note that having an object in the field of view only provides the opportunity to be irradiated but the laser must actually

have the capability to provide multiple pulses with sufficient energy to alter an object's orbit in that timeframe.

The time on target can be greatly increased if the debris object can be tracked by the laser. For very small particles, that might be more likely to be affected by the laser energy, there is no way to do this currently. For trackable objects (above about 10 cm in diameter) element sets are available to provide tracks to within 1 km. Laser site specific capabilities would then have to be used to provide a more precise track if a small spot size can be applied to orbiting objects. However, the requirement to insure that the impulse provided serves to reduce the object's orbital lifetime vice increasing it, may limit the encounter time by limiting the opportunities for illuminating the objects, as is covered in the next section. It is also important to note that for larger objects a greater impulse will be required to affect its orbit.

- **Angle of Illumination:** In order to perturb an object's orbit to cause a decrease in its orbital lifetime with high confidence the laser energy must be imparted against an object's orbital velocity. As a result, engagement of debris will have to occur at elevations well below 90° on the approaching portion of the orbit, as shown in Figure 35. Since there is a radial component to the resulting interaction, it is desirable to engage lower in the sky if possible. This constraint will significantly increase the "slant" range, thereby dramatically reducing energy on target. It also forces the laser beam to traverse the worst part of the atmospheric turbulence, which will inevitably broaden the beam in space. The constraint will also decrease opportunities to see and affect objects as the majority of the possible engagement times will not be effective for reducing the object's lifetime.

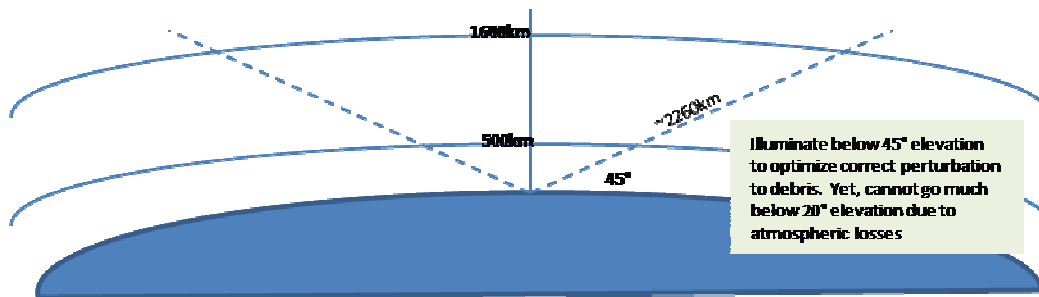


Figure 35 - Ground-based laser operations will only be effective at elevation angles below 90° approaching.

Recent analyses have shown that a wider range of elevations can be used if the debris object being illuminated is in a non-circular orbit and it is illuminated near its apogee. This geometry would produce a proportional reduction in the object's perigee altitude which will accelerate orbital decay. However, if the debris object in a non-circular orbit is acted upon by the laser closer to its perigee then the interaction will actually result in an increase of the perigee while decreasing its apogee. This circularization of the debris' orbit will result in a longer orbital lifetime.

The overall encounter geometry has shown that typical laser configurations in a stare mode will expose only tens of medium-sized debris to laser energy annually and to use higher operating illumination elevation angles of a laser one must have very accurate and precise orbital elements. Therefore, assuming effective laser interactions (which will be examined in the next section), to reach the performance threshold of ~20,000 medium objects removed per year one must have hundreds to thousands of ground sites or improve the overall laser system performance by several orders of magnitude. A similar result is calculated for removing larger objects in tracking mode – the increased time on target is counteracted by the larger impulse required and uncertainty in appropriate laser to debris geometries.

Laser Physics

Analysis of the laser physics will focus on the interaction between the laser energy and a single potential fragment. The following are critical parameters:

- **Technology Readiness Level (TRL) of laser system:** A laser must be capable of providing high energy pulses sufficient to create a recoil effect on the debris through the creation of a plasma. One very unlikely candidate for this application does exist at the National Ignition Facility (NIF) where this high peak power (~TW with a 4ns pulse) and large energy laser is capable of being fired only once a day. It is unclear whether such a device could be operated in a multi-pulse mode in the near future. More practical systems are in the 100-kW range and most of these are in the planning stages for repetition rates on the order of pulses per day where final viable designs will likely have to be able to operate at many tens of kW's and several pulses per second.

Siting these large NIF-like systems at a high altitude location will enhance the irradiance making it to the debris by avoiding much of the attenuating atmosphere. However, the higher altitude sites will be more expensive to field and operate a laser facility.

- **Effect of illumination time on altitude change:** To move a 5 gm object from 1,000 km to 300 km, where it will reenter on its own, requires a delta-v of around 150 m/s. As a result, the impulse that must be imparted to the object must be 5 gm x 150 m/s or 0.75 kg·m/s. Assuming a fluence of 28.3 J/cm² (from AFRL test results) and an impulse coupling coefficient of 2.5 dynes·s/J for a 1.06 μm wavelength laser with a pulse width of 30 ns yields a requirement for around 1,000 pulses (if the debris area is 1 cm²). With a restricted elevation range, the current technology that permits such high powered pulses to be executed one at a time, indicates the low confidence in the debris removal executing the change in orbit required. This physical effect was calculated using the 40 cm exposure area which would operationally result in statistically “never” seeing a medium piece of debris when operating in a stare mode.

Clearly, at one pulse per day this is not likely to bring any meaningful debris cleansing from low Earth orbit. Alternatively, it may be seen that several thousand site would be needed to result in even the illumination of ~20,000 medium debris objects, even assuming the higher elevation firings would be effective. It is more likely that a laser concept would try to precisely track the debris and place its energy in a small spot on the debris to maximize irradiance. However, the technology required to accomplish this precise tracking and beam control is not sufficiently developed for the small, dim objects that compose most debris. Additionally, the pulse frequency would have to be increased several orders of magnitude to even permit one site to impart sufficient energy to a single object each day.

- **Material and surface characteristics:** Orbital debris will have many and varied constituents from phenolics and epoxies to aluminum, steel, and tungsten. The shapes and surface characteristics will even be more varied as the fragmentation process will cause debris fragments to characteristically look most like “corn flakes” with uneven surfaces and inconsistent contours. Additionally, fragments produced from explosions and collisions have been seen to have a bit of black, carbon residue deposited on them from the detonation related to the fragment process. The figure below shows how aluminum is the best surface for energy coupling. All of these observations contribute to the insight that whatever laboratory

tests are conducted showing impulse coupling for bare aluminum, the actual coupling that could be realized in operations will be several of magnitudes less

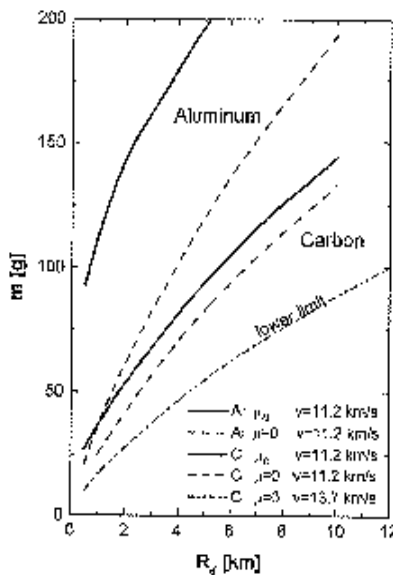


Figure 36 - Tests have shown that bare aluminum sheets couple laser energy the best but this is an unlikely target on-orbit³⁵.

- **Object dynamics (i.e. tumbling):** Just as surface characteristics of orbital debris will make the impulse coupling less efficient, so will any tumbling that the debris might be experiencing. This will detract from the optimum effects for two reasons. First, the tumbling will cause the fragment to present a different surface to the laser over time thus making it more difficult for a plasma to be created and hence, for any impulse to be generated. Secondly, with the varied orientation relative to the laser impingement any impulse created might be imparted in a non-optimum direction, further eroding any potential reduction in the orbital lifetime of fragments from laser irradiation. The magnitude of this erosion of energy coupling has not been quantified but is likely to add at least another order of magnitude reduction in efficiency.

Results

The results from the analyses of orbit geometry and laser physics are combined to yield the following conclusions regarding overall removal efficacy for lasers:

- **Laser irradiation is insufficient to remove/move objects in LEO:** The most optimistic assessments of debris exposure geometry and impulse coupling shows that even the most populous, very small debris would not be affected in any measurable way from laser illumination. Without improvements in medium debris tracking, laser beam spot growth, pulse repetition rates for high energy lasers, and a better understanding of laser-material interaction physics (such as roughness, carbon residue, and tumbling) debris removal using

³⁵ Wolfgang O. Schall, Laser radiation for cleaning space debris from lower earth orbits, Journal of Spacecraft and Rockets, 2002, vol. 39, no. 1, pp. 81-91.

laser is problematic. For larger objects, the problem is harder in many respects, since while the object would be more easily tracked, it would require a much larger impulse to remove it from orbit and laser surface interaction issues would be amplified which would thereby require significantly more engagement time from the laser system to compensate.

- **Atmospheric compensation cannot significantly improve removal effectiveness:** Analysis by AFRL suggests that a Laser Guide Star (LGS) must not only be used but must lead the small, dim debris fragment. Even this will not correct for the tilt anisoplanatism effect in the atmosphere. Overall, tracking may even be the worst problem, since the debris will generally be too dim to track to high precision, and tracking is the largest error source in laser system analyses. In summary, optimum atmospheric compensation will contribute to irradiance on target but will not be sufficient to get the irradiation even to within several orders of magnitude of what is needed. If larger objects are pursued, the tracking will be easier but the amount of energy required to be deposited on the objects will be much greater. No matter which size of debris is being pursued a breakthrough is needed in atmospheric compensation capabilities to correct for the probable several orders of magnitude increase in spot size from a state of the art laser for propagation of around 1000 km.
- **It is infeasible to increase the time on target by tracking the debris in concert with illuminating them:** While the concept of tracking an object to deposit more laser energy on it sounds appealing it is highly unlikely to provide any assistance in this application for two reasons. First, the objects in the 5mm – 10cm size range are too small to be precision-tracked by ground radars and optical sites since they cannot be reliably detected and correlated. Second, due to the geometric constraints of the required impulse on the debris the tracking should occur at relatively low elevation angles, if possible. As a result, even if tracking were likely for the short time available, it would not provide enough added irradiance to make the approach viable, since the slant range is much larger at low elevations and more atmosphere will be between the laser and the debris object. As stated earlier, there are limited situations when it might be feasible to illuminate at higher elevation angles, but these will not be typical encounters and also require enhanced orbital element set fidelity to include very accurate argument of perigee determination.
- **The current operational constraints of the Laser Clearing House (LCH) must be significantly modified:** As stated by AFRL's analysis, any laser that points above the horizon will require "shot-by-shot approval" from the LCH. With the number of pulses required to affect debris orbits the current process of the LCH would have to be substantially modified for laser removal to be allowed to operate even if the process appeared to be effective.

Summary

The use of a ground-based laser to move/remove even medium-sized (5-mm – 10-cm) debris, much less intact derelict objects, is not likely to be effective with current technology. The number of objects exposed to a laser, given the geometric constraints, coupled with the poor predicted irradiance on these limited fragments makes it mathematically unrealistic that a substantial number of objects could be moved/removed. More specifically, even using the most optimistic energy propagation energy coupling assumptions it would require the operations of many hundreds of ground-based laser sites to insure the stabilization of the lethal debris probability of collision (i.e. remove ~20,000 medium-sized fragments from LEO annually). However, if several of these issues can be simultaneously corrected while the state of the art in lasers is also enhanced significantly, the viability of laser removal of debris may be enhanced.

Yet, the coupling of laser energy to coarse, dirty, tumbling debris is an issue that requires significant analysis to even quantify its impact, much less be able to solve the problem.

Moving a laser to a space-based platform reduces the need for atmospheric compensation and potentially decreases the range to potential debris. However, the laser necessary to provide any sufficient irradiance for space-to-space ranges is not yet in existence. Hypothetical systems proposed would not provide sufficient irradiance and resulting impulse to make debris removal viable. The significant and uncertain coupling of laser energy to coarse tumbling debris will still need to be addressed for space-based applications. In short, any proposed laser concept, whether ground-based or space-based laser, must be scrutinized very closely, and our assessment is that they are unlikely to be effective for debris removal in the near future. At a minimum, a demonstration program would have to prove the viability of any concept. One technology that is currently immature is ground-based laser-plus-Space Relay Mirror (SRM), and that could present a long-term solution, since the atmosphere can in principle be well-corrected and the laser device can be on the ground. However, the debris tracking from such a platform would still have to be quite excellent and the system issues would still need to be scrutinized and demonstrated.

For both space-based and ground-based laser systems, the political and legal hurdles for their deployment will definitely be substantial.

Appendix C: Large Object Removal

The very largest objects, derelict payloads and rocket bodies, may collide with and terminate missions of operational systems when involved in a collision and the collision in turn will create tens of thousands of “lethal” fragments. It is these “lethal” fragments that will eventually be the hazard that will drive the future risk environment even though it may not be those objects that are the most critical, or advantageous, to remove first. The primary concern from orbital debris is the “residual risk” posed by 5 mm – 10 cm-sized (i.e., cm-sized) fragments. These objects are large enough to terminate a mission upon impact, cannot be seen reliably from the ground, and yet are 10-100 times more populous than the cataloged population. The practicality of the large object removal is tempered by the observation that one must remove ~10-50x derelict objects to prevent a single collision.

The larger sized, trackable objects (>10 cm) can easily be observed and cataloged and, thus, avoided if a satellite has (1) maneuver capability and an operator has (2) access to accurate conjunction data with (3) enough warning to permit a maneuver to be executed. The satisfaction of these three “ifs” is not trivial and is not common in LEO while it is more prevalent in GEO. Over fifty collision avoidance maneuvers have been performed to date, most occurring since 2008³⁶. These events are either driven by special risks (i.e. manned spaceflight) or an increased level of debris awareness in tandem with an increased perception of collision risk.

While the need for debris removal in GEO is likely to lag behind LEO, the population of GEO objects is distributed such that the highest priority objects to remove are clearly identified. In GEO, the average annual probability of collision with the trackable population for a large stationkept communications satellite is 3E-7 to 3E-6 depending on its location relative to the stable points³⁷. The objects in GEO that are “trapped” (i.e., oscillate about stable points on the GEO arc) pose a disproportionately high percentage of the collision risk to operational satellites: about 15% of the objects pose 80% of the collision hazard in GEO. Therefore, the removal of around 150 objects can reduce overall GEO collision risk by a factor of five³⁸.

Requirements for Large Object Removal

The efficacy of large object removal may be further increased by removing the objects with the largest collision threat and potential for debris creation first³⁹ & ⁴⁰. As stated previously, in GEO 15% of

³⁶ Johnson, N. and Liou, J., “A Sensitivity Study of the Effectiveness of Active Debris Removal in LEO,” *Acta Astronautica* 64 (2009) 236-243, 2009.

³⁷ Slotten, J. and McKnight, D., “Analysis of the Orbital Debris Hazard for Select US Spacecraft,” Prepared for the Space Protection Program, November 2009.

³⁸ D. McKnight, J. Griesbach, and C. Rogers, GEO Object Characterization, AMOS Technical Conference, 31 Aug-1 Sep 2009.

³⁹ Ongoing technical discussions with Nicholas Johnson (NASA/JSC) and satellite operators from 2008 to present. Joint Space Operations Center (JSpOC) has been tracking conjunctions more closely since February 2009 and reported that more than 40 collision avoidance maneuvers have taken place over the last year.

⁴⁰ McKnight, D., “DMSP Vehicle Anomaly Report (VAR) Analysis”, Prepared for the Space Protection Program, September 2009.

the objects (~150) pose 80% of the collision hazard⁴¹. Similarly, in LEO, 10 percent of the objects (~1,250) present 80% of the total collision cross-section⁴². However, it is important to not overstate the benefits of this selective debris removal. The largest object in the most densely populated region in space will not necessarily be the first object to be involved in a collision even though it has greatest probability of collision.

NASA analysis on the use of active debris removal scenarios using their LEGEND model provides one snapshot of potential efficacy of large object removal. In the scenario where NASA simulated removing five large derelict objects each year over the 100-year timeframe, the modeling predicted that 14 of 40 predicted collision events would be prevented. Therefore, in collecting (~500) large objects – in this Monte Carlo simulation - NASA anticipates preventing 14 events, i.e. about 35 objects were removed for each collision prevented. The collision probability has a probability density function whereby there is a reasonable chance that the most likely collision will not be the next collision to occur. Therefore, it is important to get as many of the most likely collision objects removed in order to actually reduce the number of future impact events. It is interesting to note that in advance of the Iridium 33 and Cosmos 2251 collision the potential conjunction of these two objects was not even one of the top 150 most likely that day and at worst was #11 on the most likely conjunction list a few days beforehand⁴³. Further, it was not even the most likely collision of the operational Iridium constellation.

In examining the satellite catalog just prior to the Iridium/C2251 collision, the product of probability of collision and mass (PC*MASS), prescribed by NASA as appropriate reasonable large object retrieval parameter, was calculated for all objects in orbit. Iridium 33 and C2251 were rated #935 and #872, respectively, as most critical to be removed from Earth orbit. Clearly, Iridium was operational so was never considered for removal. By eliminating the operational payloads from this list, C2251 moved up to about #850.

An examination of the top 100 largest derelict objects in LEO shows a convenient clumping within inclination bands that might impact the strategy for large object collection.

Inclination Range	Number
20-30°	1
30-40°	3
40-50°	0
50-60°	4
60-70°	19
70-80°	38
80-90°	6
>90°	29

Table 3 - Objects deemed “high priority for removal” are clustered at higher inclinations.

⁴¹ D. Mcknight, J. Griesbach, and C. Rogers, GEO Object Characterization, AMOS Technical Conference, 31 Aug-1 Sep 2009.

⁴² Talent, D., “A Prioritization Methodology for Orbital Debris Removal”, NASA-DARPA International Conference on Orbital Debris Removal, Chantilly, VA, 8-10 Dec 2009.

⁴³ Kelso, T. S., Analysis of the Iridium 33-Cosmos 2251 Collision, AAS 09-368, August 2009.

However, while the 70-80° range seems to be a highly populated region, a closer examination of the data provides more distinct spikes.

Inclination Range	Number	Number / Degree of Inclination
70.89-71.11°	37	~170
97.03-99.27°	19	~9

Table 4 - A large majority of the high priority objects are in a mere ~2.5° of inclination.

Clearly, the 70.89-71.11° inclination range is a viable location to first go after large derelict objects if fuel conservation is a significant part of the economic and operational model of large object retrieval. This class of objects mostly comprises Russian hardware placed in LEO. Based upon the probability of collision times mass metric (PC*MASS), these objects again are prominent. The table below lists the top 30 derelict objects in LEO by PC*MASS (largest first) from a special January 2009 Satellite Catalog provided with masses for most objects by NASA.

All but three of the entries are in one of the two inclination spikes identified above. The 70.89-71.11° band is represented well in the PC*MASS prioritized listing with ~ 70% of the objects being in that narrow inclination range.

PC*Mass	International Designator	Satellite Number	Description	Inclination	Apogee	Perigee
0.440	1998-043G	25400	SL-16 R/B	98.39	815	802
0.304	1990-046B	20625	SL-16 R/B	71.00	853	836
0.280	1993-016B	22566	SL-16 R/B	71.01	850	837
0.231	2002-056E	27601	H-2A R/B	98.58	842	737
0.226	1996-051B	24298	SL-16 R/B	70.89	861	841
0.217	1992-076B	22220	SL-16 R/B	71.00	849	828
0.192	1999-039B	25861	SL-16 R/B	97.69	651	630
0.189	1993-059B	22803	SL-16 R/B	70.99	849	825
0.168	2000-047B	26474	TITAN 4B R/B	68.00	644	558
0.168	1988-039B	19120	SL-16 R/B	71.01	848	813
0.135	2000-006B	26070	SL-16 R/B	71.00	854	829
0.131	1996-046A	24277	ADEOS S/C	98.34	797	796
0.128	1995-058B	23705	SL-16 R/B	71.02	853	832
0.127	1985-097B	16182	SL-16 R/B	71.00	843	835
0.122	1998-045B	25407	SL-16 R/B	71.01	847	834
0.121	1988-102B	19650	SL-16 R/B	71.00	851	830
0.120	1994-077B	23405	SL-16 R/B	71.00	846	839
0.116	1992-093B	22285	SL-16 R/B	71.02	846	841
0.115	1987-027B	17590	SL-16 R/B	71.00	842	832
0.113	1994-074B	23343	SL-16 R/B	98.01	651	640
0.111	2007-010B	31114	CZ-2C R/B	98.29	874	786
0.107	1994-023B	23088	SL-16 R/B	71.00	845	843
0.106	2007-029B	31793	SL-16 R/B	70.98	847	844
0.099	1987-041B	17974	SL-16 R/B	71.00	845	826
0.097	1988-039A	19119	COSMOS 1943 S/C	71.00	851	836
0.091	1991-050F	21610	ARIANE 40 R/B	98.62	764	759
0.089	1963-047A	694	ATLAS CENTAUR 2	30.37	1361	461

PC*Mass	International Designator	Satellite Number	Description	Inclination	Apogee	Perigee
			R/B			
0.087	1991-063B	21701	UARS S/C	56.97	454	356
0.086	1987-041A	17973	COSMOS 1844 S/C	70.89	868	825
0.085	2006-002B	28932	H-2A R/B	98.19	696	547

Table 5 - The top 30 high priority objects are primarily of Soviet/Russian legacy.

Interestingly, within the top 300 objects by PC*MASS (vice just 30 or 100) a different clustering of inclination bands emerges. Almost all of the 70.89-71.11° band were in the top 100 objects but the low 80° and high 90° inclination ranges rise up in importance when looking at a larger set of objects as can be seen in the table below. For the removal of up to 300 objects, these five bands contain the vast majority of all derelict objects and the 70.89-71.11° inclination band is still the most appealing place to start removing objects.

Inclination Range	Number	Number / Degree of Inclination
70.89-71.11°	40	~180
81.08-81.28°	54	~270
82.47-82.56°	63	~700
96.94-98.07°	31	~25
98.15-99.04°	54	~60

Table 6 - The five inclination bands that are most populated with “high priority for removal” objects represent only 1.5% of the entire catalog.

Figure 37 highlights the issues related to determining where to go after large debris objects first. In the region of 700-1000km the spatial density of all debris is the highest but the regions where the majority of the spatial density is due to intact hardware spikes at 800km, 1000km, 1400km, and 1550km.

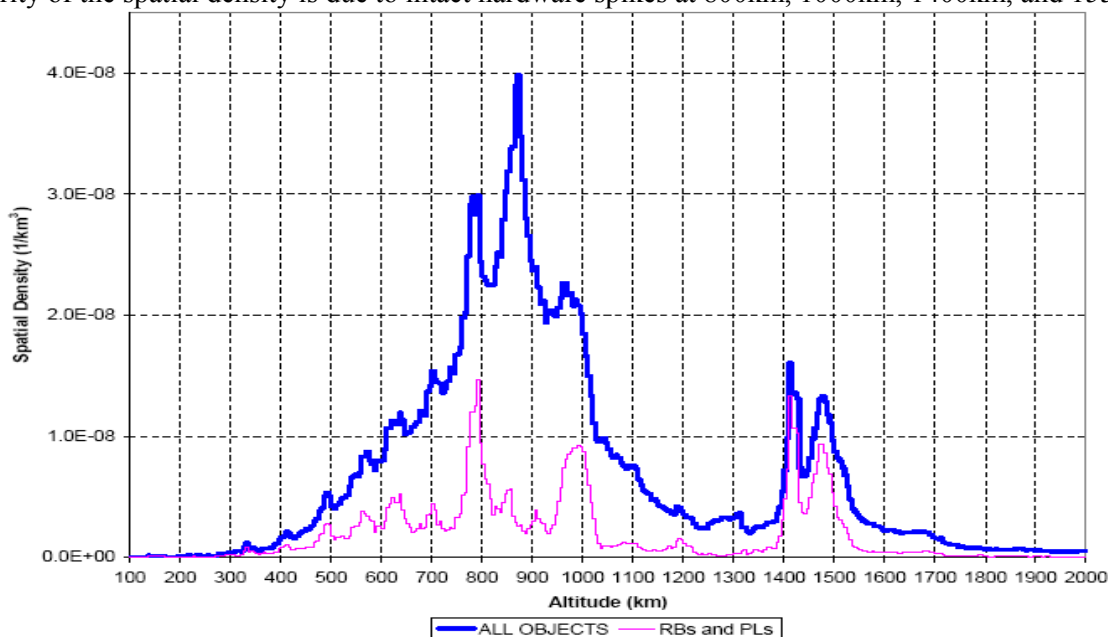


Figure 37 - The spatial density of the large derelict objects (i.e. rocket bodies and payloads) has a distinctly different distribution than the spatial density for the complete cataloged population.

Delta Velocity for Large Object Removal

The propulsion capability needed to move/remove the five groups of large derelict debris objects clumped by inclination and altitude identified above is calculated. For the analysis it is assumed that all objects are in circular orbits and are evenly distributed within each altitude and inclination range but there is no correlation between altitude and inclination within each band.

Several types of delta-V calculations are made:

- A. Moving between each of these objects only using (i) two Hohmann transfers per maneuver and (ii) using a low thrust maneuver;
- B. Synchronize with each object by (i) raising the apogee by 200 km and letting the object move underneath then returning to the circular orbit and (ii) executing a 10° plane change to synchronize with the next object.
- C. Move each object to a perigee of 500 km (i.e., move to orbit with orbital lifetime well under 25 years).

The table below summarizes the delta-V required for each band and removal type.

Group	Altitude Range (km)	Inclination Range	Number	A. Move Between		B. Synchronize		C. Deorbit	Total	
				i	ii	i	ii		i	ii
1	815-865	70.89-71.11°	40	0.039 km/s	0.050 km/s	2 km/s	50 km/s	3.6 km/s	6 km/s	54 km/s
2	750-900	81.08-81.28°	54	0.103 km/s	0.116 km/s	3.2 km/s	69 km/s	4.6 km/s	9 km/s	74 km/s
3	1000-1500	82.47-82.56°	63	0.248 km/s	0.356 km/s	3.8 km/s	78 km/s	12 km/s	16 km/s	90 km/s
4	600-900	96.94-98.07°	31	0.394 km/s	0.193 km/s	1.8 km/s	39 km/s	1.8 km/s	4 km/s	41 km/s
5	700-1000	98.15-99.04°	54	0.270 km/s	0.231 km/s	3.2 km/s	69 km/s	5.0 km/s	9 km/s	74 km/s
Total #			242	1	0.95	14	305	27	44	333
Total Mass Removed			1E6 kg	km/s	km/s	km/s	km/s	km/s	km/s	km/s

Table 7 – These nearly 250 objects constitute about 1,000,000 kg of mass – about 4% of all mass in orbit.

Making contact with each object is provided simplistically in Column A and the Column B values add the requirement to synchronize with the objects that are randomly distributed by right ascension and true anomaly. The sum of Columns A and B would be the likely delta-V required if a propulsive tug was used to attach an inflatable device, electrodynamic tether, etc. Column C is total if the propulsive tug used to rendezvous with each object is used to execute a “deorbit” maneuver.

It can be seen that the largest delta-V requirements come from the synchronization initiated by a plane change (Column B.ii). This plane change is required if it is critical to make all of these maneuvers as fast as possible whereas the synchronization by moving to a slower orbit (i.e., move to an elliptical orbit with a larger apogee) can be used if the removal of these objects can be done over a long time frame.

The time to execute any of these propulsive maneuvers depends on the mass being moved, and the I_{sp} of the propulsive system. The capability of other systems such as electrodynamic tethers or inflatables can be used to execute the Column C – deorbit activities. Additionally, some systems, such as electrodynamic tethers, may be used to move between the objects in each clump. In all of these scenarios, the delta-V to get the systems to the each clump from the ground is not included.

In summary, while the delta-V requirements shown in the table above are fairly daunting, if the maneuvers do not have to be done quickly and if there is a reasonable deorbit capability that does not require traditional propulsive capabilities then the removal of large objects does appear to be a legitimate means to manage the future growth of orbital debris.

Acronyms

AFRL	Air Force Research Laboratory
BAA	Broad Agency Announcement
BC	Ballistic Coefficient
CAD	Computer Aided Design
CONOPS	Concept of operations
CSSI	Center for Space Standards & Innovation
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
ESA	European Space Agency
GEO	Geosynchronous Earth Orbit
GNC	Guidance, Navigation, and Control
HTS	High Temperature Superconducting
JHU APL	Johns Hopkins University, Applied Physics Laboratory
JSpOC	Joint Space Operations Center
LCH	Laser Clearing House
LEO	Low Earth Orbit
LGS	Laser Guide Star
MEO	Medium Earth Orbit
NASA	National Aeronautics and Space Administration
NSSO	National Security Space Organization
ORDEM	Orbital Debris Engineering Model
RAAN	Right Ascension of the Ascending Node
RFI	Request for Information
RPO	Rendezvous and Proximity Operations
SBIR	Small Business Innovative Research
SSA	Space Situational Awareness
SSN	Space Surveillance Network
TRL	Technology Readiness Level